Chapter 4
Secondary Forests and Their Culture

Primary forests are forests that are undisturbed by significant human intervention. Thus, any human modification of a primary forest terminates its "primary" condition (fig. 4–1). The term "secondary" is applied to "forest growth that has come up naturally after some drastic modification (e.g., wholesale cutting, serious fire, or insect attack) of the previous forest" (Ford-Robertson 1971). Literally interpreted, secondary forests would appear to be only those forests that arise after virtual land clearing and would, thus, exclude cutover forests that retain a partial canopy. However, this chapter combines both types of forests under the term "secondary." Although the two may be different in structure and composition, with time and particularly as each may be subjected to management, their respective characteristics and treatments are bound to converge. Even now, the more advanced volunteer forests call for the same treatment as many cutover stands.

Of the forests that remained in 76 countries in the Tropics in 1980, at least half were secondary (Anon. 1982a). Of these, about 9 million km^2 were potentially productive (table 4–1), meaning those forests where terrain and current regulations did not prohibit the production of useful wood (but without regard to present accessibility).

Relative to population, the extent of potentially productive secondary forests in tropical America is intermediate between that of Africa and that of the Asia-Pacific region. In Africa, 72 percent of these forests are open (dry); only 28 percent have a closed canopy. In America, this relationship is 50:50; whereas, in the Asia-Pacific region, it is 6:94.

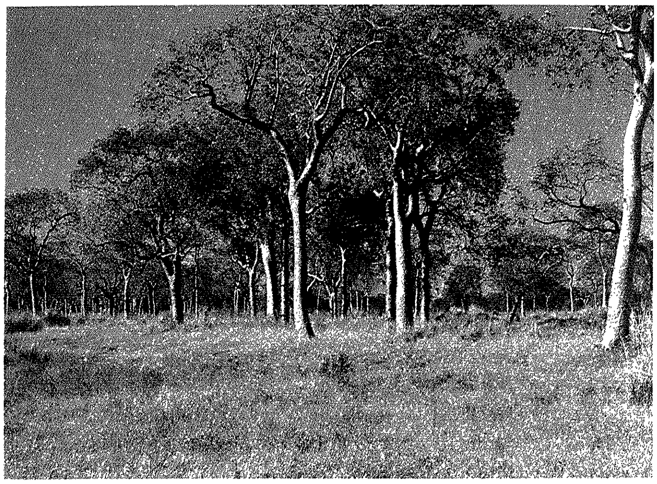

Figure 4–1.—*Residual dry forest remaining after years of overgrazing and fires; composed almost totally of* Bursera simaruba, *with no regeneration beneath.*

Existing secondary tropical forests are being lost through deforestation, but partial fellings in primary and old-growth forests are producing new cutovers classified as secondary (table 4–2; Anon. 1982e). Also, other land is reforesting naturally. The net effect has been a decrease in secondary forest area during 5 years at only about one-third the rate of primary forest decrease (Anon. 1982e).

The critical importance of current secondary forest area as a wood source in the year 2000, assuming intensified management to 6 m^3/ha/yr, is seen in figures presented by Wadsworth (1983). Because of the higher initial cost of plantations, they are much less extensive than natural forests. If, in the year 2000, plantations provide only the present proportion (12 percent) of our wood needs, we will thereafter need to exploit at least 90 percent of the remaining secondary native forests for wood. If plantations were to provide 50 percent of the timber needs, this dependence on native forests would decline to about 54 percent. However, with forest areas dwindling in the face of growing demand for the land for other purposes, the area that will be naturally regenerated and managed under sustained yield may be small in many countries.

The Nature of the Forests

There are two broad categories of secondary forest. One is residual forest that has been cut over once or more in the past 60 to 80 years, much of it within the last 30 years. Never having been completely felled, these forests retain some of their former characteristics.

The second category, termed "fallow" or "volunteer" (Anon. 1982a), is mostly volunteer growth after periodic cultivation. It lacks both the structure and the composition of the mature forest, because it is composed largely of pioneer species. About 55 percent of the secondary forests of the Tropics as a whole are cutover forests and 45 percent are fallow (volunteer). In tropical America, the corresponding relationship is 51 and 49 percent. The potentially productive secondary forest areas of the Tropics as a whole are 94 percent broadleaved and 6 percent coniferous (Anon. 1982e). In tropical America, this division is 87 and 13 percent.

Characteristics that distinguish secondary from primary tropical forests include the following (Budowski 1970, Odum 1969):

Features	Secondary Forest Characteristics Relative to Primary Forest
Nutrients and stability	
Inorganic nutrients	Extrabiotic, rather than intrabiotic
Mineral cycles	Open, rather than closed
Nutrient conservation	Less effective
Nutrient exchange with environment	More
Nutrient role of detritus	Less important
Food chain pattern	Linear, rather than weblike
Stability	Poor
Structure	
Biomass supported per unit of energy flow	Less
Size of organisms	Smaller
Upper canopy surface	More uniform
Stratification	Less organized
Lower tree stratum	Denser
Organic matter	Less
Tolerance of dominant species	Much less
Diversity	
Number of species	Fewer
Spatial heterogeneity	Less organized
Equitability of species	Lower
Niche specialization	Less
Symbioses	Less developed
Natural range of dominant species	Wider
Growth, regeneration, and productivity	
Growth selectivity	For rapidity
Regeneration of dominant species	Much less common
Seed viability	Longer
Life cycles	Shorter and simpler
Gross production	Higher
Gross production/ respiration ratio	Greater than 1
Net primary production	Higher
Wood density	Less
Wood production	More

Other differences have been noted. In Trinidad, a secondary forest had a number of species that are characteristic of habitats drier than primary forests, fewer Leguminosae and Myrtaceae, and more Rubiaceae (Greig-Smith 1952). Herbivorous insects have been found to be 5 to 10 times more abundant in secondary forests than in primary forests (Janzen 1975), suggesting that the pioneers have fewer chemical defenses and dedicate more energy to growth. In Malaysia, for instance, secondary forests, lacking the predatory and parasitic insects of primary forests as controls, proved to be a major source of cocoa pests (Conway 1972). In Mexico, trees of secondary forests tend to use more energy for reproduction than for structure building, with many seeds per plant, wide dispersal, seed dormancy in the soil, and continuous seed production throughout the year (Gomez-Pompa and Vazquez-Yanes 1974). One hypothesis is that secondary forests may have deep, diffuse roots that concentrate nutrients dispersed through burning and leaching (Stark 1971).

Residual Forests. More than half the secondary forests of the Tropics have been cut, most of them selectively as opposed to clearcut (fig. 4–2). This has reduced the representation of the most valuable species and damaged some of the remaining trees, detracting from their potential productivity of useful wood.

Impacts of logging damage have been assessed in several tropical areas, chiefly in the Eastern Hemisphere. Reports commonly emphasize the number or proportion of the trees damaged; whereas future productivity depends on the opposite effect: the number and quality of the remaining trees (fig. 4–3). A study in Sabah of a dipterocarp forest (Nicholson 1958a) showed that trees 10 cm in d.b.h. or more left undamaged decreased from 76 percent to 42 percent as basal area removed increased from 2 to 10 m^2.

In Peninsular Malaysia, the harvesting of lowland dipterocarps to a diameter limit of 58 cm damaged 39 percent of the land area and 28 percent of the remaining trees between 10 and 39 cm in d.b.h. (Wyatt-Smith 1962a). Of the merchantable species, 56 percent of the saplings from 3 m tall and up to 5 cm in d.b.h. (173 trees per hectare) remained undamaged. Of the poles from 5 to 19 cm in d.b.h., 32 percent (210 trees per hectare) remained (fig. 4–4). Of the trees from 20 to 39 cm in d.b.h., 21 percent (35 trees per hectare) remained. And of those 40 to 58 cm in d.b.h., all 10 trees

Table 4–1.—Potentially productive secondary tropical forests, 1980

Region/country	Cutover forest (million ha)	Forested fallow (million ha)	Total (million ha)	Forest (%)	Land (%)	Area per capita[a] (ha)
World	494.110	402.02	896.13	37	18	1.40
Tropical Africa	213.800	165.98	379.78	46	17	2.00
Tropical Asia	108.170	73.22	181.39	44	19	.80
Tropical America[b]	172.140	162.82	334.96	31	20	1.30
Belize	.800	0.53	1.33	68	58	8.30
Bolivia	12.090	1.10	13.19	19	12	2.60
Brazil	130.650	100.62	231.27	37	27	2.00
Colombia	.900	8.50	9.40	16	8	.40
Costa Rica	.770	.12	.89	46	17	.40
Cuba	.800	.70	1.50	77	13	.10
Dominican Republic	.190	.27	.46	51	10	.09
Ecuador	.110	2.35	2.46	14	9	2.80
El Salvador	.010	.02	.03	19	1	.01
Guatemala	1.210	.30	1.57	32	14	.20
Guyana	1.350	.20	1.55	8	7	1.90
French Guyana	.150	.08	.23	3	3	3.80
Haiti	.010	.04	.03	56	2	.01
Honduras	1.190	.68	1.87	40	17	.70
Jamaica	.004	.16	.16	70	14	.08
Mexico	.300	26.00	26.30	35	13	.40
Nicaragua	.150	1.37	1.52	28	12	.60
Panama	.820	.12	.94	22	12	.50
Paraguay	2.480	3.27	5.75	16	14	2.00
Peru	6.000	5.35	11.35	15	9	.70
Suriname	.420	.27	.69	4	4	1.40
Trinidad/Tobago	.130	.06	.19	76	40	.20
Venezuela	11.610	10.65	22.26	49	24	1.70

Source: Anon.1982e.
[a]Per capita figures based on 1980 total population.
[b]Open woodland figures available for Brazil only.

per hectare remained. In all, 255 trees per hectare of 5 cm in d.b.h. or more remained undamaged.

The removal of 11 trees per hectare from dipterocarp forests in Kalimantan, Indonesia, seriously damaged 30 percent of the land area (Abdulhadi and others 1981). The number of trees was reduced from 445 to 259 per hectare and the mean basal area from 36 to 17 m²/ha. Of the 259 trees per hectare remaining, 154 (59 percent) were undamaged. A study in Nigeria showed that removing 2.3 m²/ha of basal area left 84 percent of the remaining trees undamaged, but removing 9.2 m²/ha left only 44 percent undamaged (Redhead 1960a). Of the trees damaged, about 25 percent were injured only in the crown or bark. Such damage, although possibly sufficient to preclude further production of usable wood, was not considered a cause of early mortality. About 20 percent of the damage was caused by crawler tractors, a source more controllable than felling.

In the rain forests of Queensland, Australia, logging in stands with basal areas up to 80 m²/ha has left as much as 50 m²/ha, a third of which is made up of cabinet woods or other marketable species (Henry 1960). Such residual stands have been considered adequately

Table 4–2.—Annual change in potentially productive secondary tropical forest area, 1975–80

Tropical region	New conversion (million ha)	Reforested fallow (million ha)	Deforestation (million ha)	Net change (million ha)	Net rate of change (%)
Africa	+.64	+.95	−3.45	−1.86	−.5
America	+2.00	+1.54	−4.37	−.83	−.2
Asia-Pacific	+1.76	+.90	−1.51	+1.15	+.6
World	**+4.40**	**+3.39**	**−9.33**	**−1.54**	**−0.2**

Source: Anon. 1982a.

stocked. In fact, partial felling has only a minor impact on the rain forest environment, and its effects are quickly overcome (Anon. 1983c). Logging was reported neither to significantly extend stand recovery times nor to impair future production. Species diversity was reportedly better in logged than in virgin stands.

In Suriname, after attempts to apply the Malayan Uniform System (removing all trees down to 10 cm in d.b.h.) were unsuccessful in bringing on new regeneration, efforts to minimize logging damage to the immature trees left a residual stand that was adequate for a later second crop (Jonkers and Schmidt 1984). Despite expected further losses of up to 40 percent of the commercial trees, a crop of 19 trees per hectare, 30 to 50 cm in d.b.h., was expected to be harvestable in 20 years.

The partial cutting system developed in Suriname, designated "celos," predicts a yield of about 20 m^3/ha of quality timber every 20 years by maintaining a high level of biomass to prevent leaching of nutrients (de Graaf 1986).

In the moist foothills of Dominica, West Indies, studies of 62 0.1-ha plots showed that logging of the overwhelmingly dominant species, *Dacryodes excelsa,* left regeneration adequate for the next crop (Bell 1976). The remaining stand, ranging in basal area from 17 to 25 m^2/ha, was about 40 percent *Dacryodes* but also contained other commercially desirable species such as *Byrsonima spicata, Sterculia caribaea,* and several *Lauraceae.*

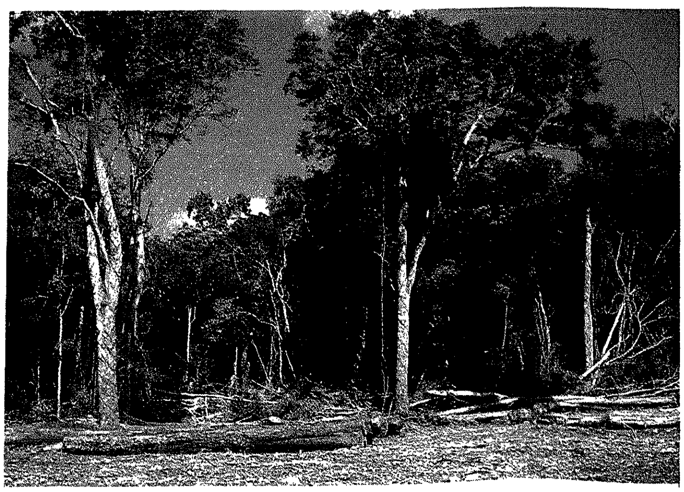

Figure 4–2.—*Residual forest in southeastern Mexico showing the density of the remaining cover.*

Figure 4–3.—*Moist forest in the Philippines immediately after logging showing remaining stand of small trees.*

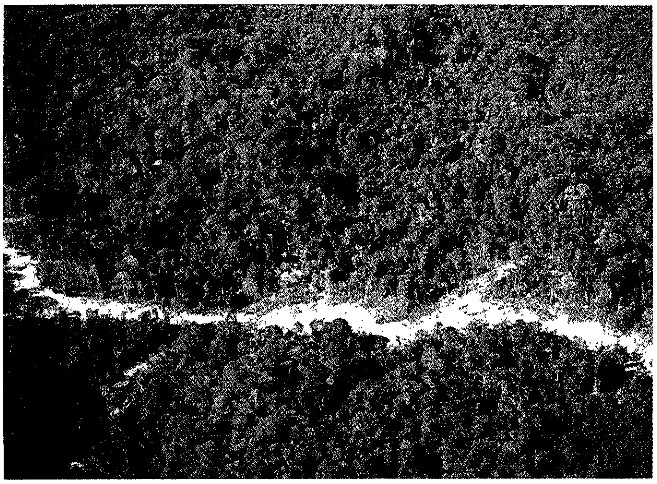

Figure 4–4.—*Residual hill dipterocarp forest in Sarawak, 18 months after removal of an average of 38 m³/ha, showing the preservation of forest cover of future potential.*

These examples suggest that logging may leave sufficient trees for a second crop, especially if logging damage is minimized through close control of field operations (Wyatt-Smith 1963). The use of high lead or cables and winches may cause less damage than tractor skidding.

However, timber harvesting may deteriorate the site even where the residual stand is adequate. Selective species removal may reduce the diversity (and conceivably the ecological stability) of the remaining forest. In one example, removing all stemwood (without bark) from moist forests eliminated 10 percent of the nitrogen (N), 39 percent of the phosphorus (P), 28 percent of the potassium (K), 20 percent of the calcium (Ca), and 57 percent of the magnesium (Mg) from the ecosystem (Ewel and Conde 1978). Even if removal is not complete, such losses, together with expected lower rates of infiltration, may threaten the quality of the site. After logging in one area in Kalimantan, Indonesia, infiltration of rainwater into the soil declined from 4.6 to 0.6 cm/min (Abdulhadi and others 1981).

However adequate the residual stand may be, its value is of little importance where abandoned logging roads invite cultivators to move in and fell what is left to convert the area to food production.

Fallow or Volunteer Forests. Where forests have been completely removed but the climate and soils still favor forest growth, the cessation of human disturbance allows gradual reestablishment if tree seeds reach the area. These forests may be deliberate agricultural fallows but, in any case, are volunteers. They resemble primary succession and usually differ significantly at the outset from the forests that preceded them.

Recovery Through Succession. Secondary forests, whether residual or volunteer, are continually changing through succession, a process whereby organisms better adapted to the redeveloping forest environment progressively replace the organisms of previous stages. Succession follows a pattern, is community controlled, reasonably directional, and therefore predictable. It culminates in a stabilized ecosystem in which maximum symbiotic function among organisms is maintained (Odum 1969). Succession increases the overall stability of the forest as an ecosystem and leads to increased resistance to disturbances. For timber production, successional forests more closely simulate rain forest behavior than do "steady state" forests (Anon. 1983c).

Four phases of forest succession in the broadleaf forests of the North Temperate Zone (Bormann and Likens 1981) appear to be relevant to the Tropics. These are as follows:

1. Reorganization, during which total organic matter declines despite an increase in living biomass
2. Aggradation, during which the system accumulates biomass and litter up to a peak
3. Transition, during which biomass and litter decline somewhat
4. Steady state, when biomass and litter fluctuate about a relatively constant mean.

During reorganization, dead organic matter from the former system is decomposing and disappearing more rapidly than biomass is being formed. Biotic regulation of water is established promptly, but rates of dissolved nutrient loss may exceed those of primary forests for a long period.

During aggradation, a modest but nearly constant excess of primary production over decomposition produces a high rate of biomass and litter accumulation. Resistance to export of nutrients is at its peak. Nitrogen accumulates from both precipitation and fixation. Also, the chemical components of drainage water and erosion are closely regulated. Streamflow is reduced, thus conserving nutrients. Interception and transpiration lower the quantity of stored water.

During transition, the rapid early rise in primary productivity that increases biomass declines with the shift to species that are slower growing but more efficient in exploiting the changing environment.

The steady state is a shifting mosaic in which patches are in different stages of development involving sequences of biomass accumulation and loss. Habitat diversity rises to a maximum. Species richness is greater than during aggradation, but in forests cleared only briefly, the richest diversity of flora may occur in the early phase, combining sprouts of the past advanced forest with seedlings of pioneers.

The composition of pioneer stands may indicate both the past and present environment (Hall and Okali 1979). Some species reflect the intensity of past land use, others, the quality of the soil. Small differences in the original environment observed in Suriname (such as concave relief) caused a remarkable divergency in succession (Boerboom 1974). Studies in wet areas of Mindanao, Philippines, on the other hand, led to the conclusion that there are also many environmental variables not correlated with vegetation (Kellman 1970).

Succession usually begins with species that, although uncommon in the stable forest, colonize major openings (fig. 4–5). Four common characteristics of such species contribute to their success during forest succession (Bormann and Likens 1981): (1) large quantities of viable seeds dormant on the forest floor, (2) germination triggered by disturbance, (3) rapid height growth, and (4) relatively rapid reproduction and reestablishment of a dormant seed pool.

Some pioneer species have such a sharply defined role that although 50 percent or more of the seeds may germinate in the light, none germinates in the shade (Vazquez-Yanes 1976). Examples are some tropical tree species of the following genera: *Cecropia, Clidemia, Myriocarpa, Solanum, Trema,* and *Urera*. Within the genus *Piper,* species common to secondary forests require light for germination, unlike those found in primary forests.

Figure 4–5.—*Gap regeneration by the opportunist* Cecropia spp., *following a hurricane in Puerto Rico, beneath which a mixed forest returns.*

The pioneer species that comprise early successional forests are especially adapted in other ways. Many depend on and immobilize a flush of nutrients such as may result from logging residuals immediately after cutting. *Trema,* a pioneer genus in cutover forests in Malaysia (also present in tropical America), grows poorly on degraded soils, apparently requiring abundant nutrients (Wyatt-Smith 1949c). Possibly for the same reason, *Musanga* in Malaysia (like *Cecropia* in America) comes up in abundance immediately after clearing but is less common following a period of farming (Baur 1964b). In Nigeria, *Musanga* still comes up after the first year of farming but is less plentiful after 2 years (Lamb 1940).

Rapid growth of pioneer species may not result purely from efficiency of energy conversion or dry-matter production. For *M. cecropioides,* such growth results from a capacity for unrestricted node elongation, leaf production, and an efficient branching pattern (Coombe and Hadfield 1962).

Pioneer stands in moist climates may be able to dominate grass but not the trees that come up beneath them. An example is seen in Malaysia where *Mallotus* and *Macaranga* quickly form a high canopy that can suppress *Imperata* grass but not woody species (Wyatt-Smith 1949c). The light canopy of most pioneers favors the regeneration and growth of the species that succeed them, although in Sabah, *Anthocephalus* reportedly may suppress dipterocarps (Meijer 1970).

Pioneer tree species generally do not live long. A species of *Trema* in Malaysia commonly lives only 2 years (Wyatt-Smith 1949c). Many pioneer trees in Brazil decline after 10 to 15 years (Weidelt 1969). *Cecropias* more than 25 years old are rare and decadent. In Sabah, only one pioneer, *Anthocephalus,* lives as long as 40 years (Meijer 1970).

Succession is progressive, with the initial conditions that favored pioneer species gradually subsiding. In the early stages, high rates of reproduction and growth are rewarded with success. Later, with increasing biomass, the ecosystem is characterized by greater internal competition (Odum 1969).

The transition that takes place during tropical forest succession is illustrated by early observations in what is now the Central African Republic (Aubreville 1948). In a primary forest with no *Musanga,* there were, nevertheless, 125 seeds per square meter of this species on the forest floor. With release, they germinated and grew rapidly for 10 years to 20 m in height. Some understory species of the primary forest then entered beneath them. Then, a second group of light-demanding trees with soft woods entered and surpassed the *Musanga.* Finally, shade-tolerant trees of the primary forest grew up through this secondary vegetation, while an understory of primary forest developed beneath.

In the early stages of succession, secondary forests apparently allocate growth first to leaves and then to stems and roots (Ewel 1971). In a Panamanian wet forest clearing, the greatest growth in leaf biomass took place during the first 2 years, whereas the greatest stem growth occurred in the 3rd and 4th years, and the greatest root growth was in the 5th and 6th years (table 4–3).

Table 4–3.—Biomass growth allocation in a secondary tropical forest in Panama (t/ha/yr)

	Age interval		
Biomass unit	0–2 yrs	2–4 yrs	4–6 yrs
Leaves, flowers, and fruits	1.8	1.2	0.3
Stems	4.7	11.3	2.0
Roots	1.3	1.0	4.8
Total live biomass	**7.8**	**13.5**	**7.1**
Litter	2.3	.6	.2
Total	**10.1**	**14.1**	**7.3**

Source: Ewel 1971.

An increase in the number of tree species is characteristic of forest succession unless sprouts from the previous forest remain. During an 11-year period in a secondary forest in Costa Rica, the number of arborescent species increased from 10 to 54 (Fournier and Herrera de Fournier 1977).

The rate of succession is the rapidity with which a secondary forest approaches stability. Criteria include nutrient and organic matter levels in the soil, canopy density, basal area, and volume or biomass. A secondary forest in Suriname, arising after deforestation and debris removal or burning, attained from 40 to 70 percent of the basal area of the primary forest in 7 years (Boerboom 1974).

Rapidly growing tree species with soft wood followed herbaceous vegetation the 2nd year after shifting cultivation in lowland Guatemala (Snedaker 1970). As these species matured, they were slowly replaced by species with denser wood. Aboveground standing crop increases after the 1st year were the result of stemwood growth. There were no discernible changes in leaf biomass during the first 10 years of succession. By the 3rd year, light transmission had declined to 5.4 percent, where it stood for the next 11 years. At age 14, the interception of precipitation was approximately as shown in table 4–4.

The recovery of soil under a secondary forest is probably as good a measure of progress toward a steady state as are the characteristics of the vegetation. One crude measure is the increased porosity of the soil as the forest

Table 4–4.—Precipitation interception in a 14-year-old secondary forest in Guatemala

Precipitation (cm)	Interception (%)
0.20	40
.40	20
.85	17

Source: Snedaker 1970.

develops. As a result of reforestation in the rain forest region of Nigeria, the bulk density of the soil rose above that of the mature forest, but the former lower level was restored in 10 years (table 4–5) (Aweto 1981b). Water-holding capacity dropped 35 percent after clearing, but one-third of that loss was restored in 10 years. In the same forest, organic matter content in the first 10 cm of soil dropped more than half with clearing, but 60 percent of the loss was regained in 10 years.

In wet forests of Colombia, above- and below-ground N losses due to deforestation, some 1,300 to 1,400 kg/ha, were restored by N fixation at rates of 100 to 150 kg/ha/yr (Salas and Folster 1976). It was predicted that losses of K, Ca, and Mg might be restored in 20 years or less.

In the humid forest region of the lowlands of eastern Guatemala, litter accumulation beneath a secondary forest was found to reach half that of a stable forest in less than 1 year (Ewel 1968). The input of organic matter by the 11th year exceeded that of the stable forest, peaked near 21 years, and returned to the level of the mature forest after 30 to 35 years. Organic matter accumulation in the soil attained the rate of a mature forest during the first 3 to 5 years of fallow (secondary forest) and then increased. Restoration of N inputs increased with age but was never higher than in the mature forest. Phosphorus input rose with litter production, reaching half the level of the mature forest in 5 weeks. Because of large quantities of accumulated Ca and Mg, inputs of these nutrients from a young secondary forest may be insignificant and not clearly related to stand age. In a later study, litterfall increased at a rate of 10 t/ha/yr up to the 14th year, at which time it equalled that of the mature forest (Ewel 1976). The apparent causes of the increase were greater deciduousness and changing species. This study also showed that the nutrient content (N, P, K, Ca, and Mg) of the litter during the first 6 years equalled that of the mature forest.

Secondary forests accumulate organic matter rapidly when used as fallow for shifting cultivation (Ewel 1968). Studies in Guatemala showed that the return of N is relatively constant and moderate amounts can accumulate in the new litter very early. Ewel surmised that this increase is the primary benefit of fallowing for the next crop. The increase of P is closely related to litter production. More than 75 percent of the P stored in the litter at the time of clearing remains 6 months later. Levels of K, Ca, and Mg are not clearly related to the age of the fallow. Potassium is rapidly cycled, with little or no accumulation, and Ca and Mg are relatively stable in accumulated storage.

The fate of the timber species in successional forests is of special interest. The natural outcome of succession is high biomass relative to productivity, whereas wood producers strive for high productivity per unit of biomass (Odum 1969). Under favorable circumstances, timber species may regenerate after cutting. In the Gambari Reserve in Nigeria, in a tract exploited for both timber and fuel, the number of seedlings of useful species increased in 4 years from 4 to 38 per hectare, and the number of saplings from 2 to 47 (Mallam 1953). Many of the seedlings were from seeds that germinated after the felling.

Timber species that are seral, adapted only for an intermediate successional role, may be forced out by natural succession before they mature. Useful (but seral) species of genera such as *Ceiba, Terminalia,* and *Triplochiton* were declining in a 14-year-old secondary rain forest in Nigeria (Keay 1963). Their growth below the canopy was slow. In contrast, the canopy species were either being maintained or increased. It was concluded that a

Table 4–5.—Restoration of soil porosity in a secondary forest in Nigeria

Forest age	Bulk density (g/cm^2)	Total porosity (%)	Waterholding capacity (%)
1 year	1.19 ± 0.01	54.4 ± 1.0	36.4 ± 0.6
10 years	0.98 ± 0.02	63.0 ± 0.8	46.5 ± 1.2
Mature	0.98 ± 0.01	63.2 ± 0.3	56.3 ± 2.1

Source: Aweto 1981b.

secondary forest without cultural treatment will produce little usable wood.

The Environment for Production

The significance of secondary forests to human society in the Tropics is traditional. Tropical farmers have for millenia depended on secondary forest fallows to restore productivity to land worn out by cultivation. A classic example is to be seen in the mangroves of Papua New Guinea (Gray 1960). The mangrove trees yield wood for shelter, fuel, and dugout canoes. Adjacent sago palms provide starch. Protein comes from marine life dependent on the mangrove. Less direct but equally significant human dependence on forests is evident in: (1) urban needs for water from forested watersheds and for industrial wood products, (2) irrigated agriculture, dependent on a continuous supply of sediment-free water, and (3) national economies, dependent on exports (or the avoidance of imports) of wood products.

General Perceptions. Making secondary forests produce usable wood in the Tropics has benefits but also costs. The employment created, entirely rural and mostly unskilled, is well adapted to social needs. However, prospective yields may be distant in time, geographically diffuse, and still largely unpredictable. Commonly seen drawbacks to tree production are its long-term nature relative to other investments and apparently limited compatibility with the practice of agricultural fallowing.

The superficial appearance of secondary tropical forests, with few large, straight trees of marketable species, suggests that they are nearly worthless economically and merit little or no managerial investment. The area of potentially productive tropical forests being managed in 1980 was insignificant (table 4–6; Anon. 1982a). A subsequent report puts the total area of moist forests in tropical America under sustainable management systems as 75,000 ha, all in Trinidad (Poore and others 1989). Nevertheless, wherever such forests are extensive and likely to persist, their social and economic potential warrants comprehensive assessment to explore their suitability for more intensive management.

Leslie (1987a), in evaluating the desirability of natural forest management, states that a clear distinction needs to be drawn between economic and financial feasibility. Economic feasibility includes all returns and all costs and may well prove more promising than the less comprehensive, direct financial feasibility. Wyatt-Smith (1987a) concludes that, although much of the future industrial wood will be produced by planted forests, the larger area suited only to natural forests is a fallback option.

C.T.S. Nair (1985) points out that the multiple values of natural tropical forests are seldom fully utilized in management. He sees a general tendency, where such values are recognized, for land-use segregation, subordinating most potential uses on any one forest area.

Despite widespread opinion that cutover and volunteer forests have little potential, there are foresters who see promise in such stands if treated early. For example, Plumptre and Earl (1986) conclude that tropical forests can produce far more without changing their essential nature or their capability to harbor forest fauna. To leave such forests without treatment after exploitation, they say, is to condemn them to inevitable, slow degradation. By developing small forest industries and applying appropriate silvicultural treatment, managers can probably make some of these forests profitable, particularly if their nontimber benefits are recognized. The understanding of secondary tropical forests is not in its infancy. More than a century of experience has yielded

Table 4–6.—Management status of closed tropical forests in 1980

Region	Potentially productive (thousand km²)	Managed (thousand km²)	Proportion managed (%)
Tropical America	5,217	5	0.1
Tropical Africa	1,630	17	1.1
Tropical Asia	2,010	398	19.8
Total	**8,857**	**420**	**4.7**

Source: Anon. 1982e.

much information concerning these forests and their culture. Beginning in 1880, thousands of hectares of natural forests were refined in southeastern Asia. During the first decade of this century, management of mangroves was developed in what is now Malaysia, and the "coppice with reserves" system was applied to dry forests in India for poles, fuelwood, and fodder. Tests of natural regeneration began on a large scale in Nigeria.

In the 1920s, high early mortality of natural regeneration in tropical forests was documented in what is now Sri Lanka, and problems with girth limits, in terms of unreliable regeneration, came to light in India.

In the 1930s, tropical shelterwood testing began in what is now Malaysia. Fellings in the underwood in India were found not to induce what was considered adequate regeneration of the few species then wanted. Pioneer species such as *Musanga* were found to be an asset as nurse trees in what is now Malaysia.

In the 1940s, the short lives of pioneer species became known as did the virtue of following natural succession in stand treatment.

In the 1950s, the level of stored nutrients in forest fallow was found in Ghana, with nearly complete site recovery in 14 years in Nigeria. There the rapidity with which the useful tree species return in secondary forest was documented. The Malayan Uniform System and the diagnostic-sampling technique were developed in what is now Malaysia. Significant growth rates of trees of desirable species, even in untended forests, were discovered in Australia. In Brunei it was concluded that simplifying natural forest composition does not prohibit sustained yields. The selection system was applied in the Philippines; but in Uganda it proved inadequate because of cumulative felling damage and slow growth. Nevertheless, it was found that most selected and tended crop trees survived and that only a few were needed for full stocking.

In the 1960s, it was found that logging damage in Nigeria could be significantly reduced through greater care. Dynamic sampling techniques were developed in Uganda. Potential yields were determined for many tropical areas.

Since 1970, more basic new information has been developed in both tropical hemispheres. Regeneration has been studied from the phenology of flowering through seed dispersal to storage in the forest and establishment relative to illumination and other conditions. A high proportion of the nutrients has been found to be within the vegetation. Nutrient cycling and some of the effects of interventions have been documented. Intensified study of forest fauna has shown a role critical to the well-being of forests. New knowledge of the interdependencies of animals and plants within the forests has shed light on the fragility of many species and the corresponding effects of modifications. Conservation of biodiversity has been shown critical to good forest management. Evidence is accumulating that secondary forests contain more potentially useful trees than heretofore thought. Wide variation in the growth rates of apparently similar trees suggests greater productivity potentials from enlightened liberation.

Nevertheless, in spite of the early accumulation of knowledge, natural forest management was abandoned in many tropical countries, particularly during the 1960s and 1970s, mainly because of shortages of trained staff and inadequate financial resources (Masson 1983). Even the 5 percent of closed tropical forests classified as "under management for production" for the most part is not being intensively managed.

Developments during the 1957–1982 period that have affected the management of mixed tropical forests include the following (Masson 1983):

- Increased population and sustained deforestation for shifting cultivation
- Increased importance of forests to rural communities
- Increased demand for fuelwood and industrial wood to a point where existing management cannot consistently supply needs
- Logging systems requiring large-scale operations and removal of more species and smaller trees, beyond the capacity of forestry staffs to control damage and integrate needed silviculture
- Short-term forest enterprise contracts with no long-term productivity incentives
- Public funding on an annual basis, inhibiting forest culture for the long term.

Even with careful selection cutting and extensive liberation treatments, yields have been so low that it is difficult to convince governments that combined social and economic benefits, including employment and foreign exchange, justify protection or even preservation of mixed tropical forests.

The sequence of events in Nigeria illustrates the results of this perception (Lowe 1984). Forest reserves originated in 1899, and by the mid-1920s, systematic silvicultural research was in progress. By 1950, some 2,000 km^2 had been treated by tropical shelterwood methods. By 1970, hardwood exports were prohibited in an effort to favor the local market. By 1980, even though it had been shown that natural high forests could produce 1 m^3/ha/yr on a 40-year rotation, the remaining forests were considered insufficient to meet local needs and some 110,000 ha were planted. Lowe concluded that after 50 years of efforts, sustainable yields are achievable but natural regeneration is still insufficiently understood.

Experience with the management of natural forests indicates that there will be a continuing place for such forests where land resources are adequate and rational treatments are applied (Mergen and Vincent 1987). The importance of forest plantations to future timber supplies is recognized, however, as are the remaining uncertainties about silvicultural practices under many forest conditions. An impression remains, nevertheless, among those who have worked with the forest, that cutover stands can be made to yield far more than has been evidenced to date.

Heartening conclusions for productive rain forest management came from experience in Queensland, Australia (Anon. 1983c). Selective logging was found compatible with multiple-use management of such forests. Strong growth response followed logging. Logging cycles of 40 to 50 years could be sustained. Logging at normal intensities did not increase species loss. Visual impacts of logging were short lived. An immense regeneration potential existed.

Past silvicultural treatments have been mostly trial and error, bringing to light the complexities of such forests and the need for more technical information. Silvicultural practices formerly widespread have been abandoned. Initially, hesitation to depart from nature led to treatments so conservative that little growth acceleration ensued. The large openings found necessary to stimulate crop trees in Suriname, for instance, also stimulated competitors (Anon. 1959j). Bold treatments were found necessary in Uganda, but sometimes even they failed, suggesting that unresponsive trees were stagnated by long suppression (Dawkins 1963b). The discovery that response to liberation is greatest in small trees suggested that a growth rate "pecking order" for each tree may be set at an early age and that it lasts for life (Lowe 1966). This may partly explain the difficulty in selecting prospectively fast growing trees on the basis of outward appearances.

Past silvicultural treatment of secondary forests has accelerated growth, but single treatments do not ensure sustained yield. Early treatments, widely termed "improvement fellings," were recognized as only provisional, because the main objective was merely to utilize the available stock (Troup 1921). Although a sequence of treatments would be expected to increase the proportion of seedbearers of desirable species and periodically open the forest enough to induce regeneration, there is as yet no evidence that such a process is generally a reliable source of future crops. As a result, efforts are likely to be concentrated instead on breeding superior plantation trees, further increasing the productivity of plantations.

In refining secondary tropical forests, foresters select crop trees according to their prospective marketability, present size relative to maturity, form, freedom from injuries, and apparent health. Even where many tree species may be acceptable for future products, management tends to reduce the number of species, always favoring species thought to be the best. An extreme result could be to reduce forest diversity to near species purity in local areas. This might eventually eliminate all species adapted to certain microsites to which other, more desired, species might later prove unadapted. More diversity than required for maximum timber productivity may be necessary to preserve the site and ensure the well-being of the forest. Where such information is not available, silviculture can only be provisional and should modify stands only cautiously and gradually.

Support for managing secondary tropical forests for timber is seen in the conclusions of Wyatt-Smith (1987b). He states that plantations should not be seen as an alternative to tropical moist forests because products yielded are different. Few high-quality woods, with the notable exception of teak, grow well in plantations, and conversely, mixed industrial grade woods from tropical moist forests are greatly inferior to the uniform products of plantations. Thus, managing for sustained yield as large an area of tropical moist forests as possible is recommended.

Wyatt-Smith further concluded that the increasing use of veneers and reconstituted wood rather than solid wood, the use of stains and other devices to produce decorative faces, the use of many more species (including formerly "weed" species), and the technical developments that have greatly reduced waste all influence policy decisions. However, he stated that there will always be a market for prime, solid timber and that the price for such timber of preferred species will increase greatly in excess of inflation in the face of reduced supplies. As a consequence, Wyatt-Smith saw it unlikely that there will be any economic risk in favoring tree species that regenerate easily, grow reasonably fast in relatively pure stands, are relatively free of disease and insect attack, do not cause site deterioration, and produce good-quality timber.

Leslie (1987a) concluded that it is not necessary to defend natural forest management because the economic case against it could be wrong or simply because of its inherent theoretical and practical weaknesses. He saw it to be wrong because, at the interest rates suggested for use in forest economics studies, natural management of tropical mixed forests is likely to be better financially than alternative land uses or management systems. Natural management, he concluded, wherever it is ecologically feasible, is also economically preferable on its own merits.

Public concern over the feasibility of producing timber crops economically is in part a result of management failures for other than technical reasons (Schmidt 1987). Other causes of failure include a lack of protection of the property from trespass; abandonment due to availability of already mature timber elsewhere; the promise, often unfulfilled, of higher yields from plantations; inadequate or inconsistent financing; and political instability.

Stand Complexities. Without silvicultural intervention, natural succession in cutover forests very slowly approaches the characteristics of primary forests. Left to nature, secondary forests on all but the poorest sites will usually eventually produce some trees of marketable species, size, and form. The rapidity of this process depends on climate, soil, and the severity and duration of past modifications of the forest, as well as on proximity to seed sources and fauna responsible for seed dispersal.

Whitmore (1983), in a review of secondary succession from seeds in tropical rain forests, pointed to the complexity of the process and gaps in our knowledge. The presence of seeds of pioneer species beneath forests is now generally recognized. Whitmore rejected the separation of species into two groups: pioneers and climax. He saw a continuum from one extreme to the other. Differences in the size of forest gaps, the time that they persist, their causes, and their proximity to seed sources all influence the course of succession. Disturbances due to logging may vary widely from place to place, leaving a mosaic of conditions for subsequent succession.

Although the diversity of secondary forests may be less than that of primary forests, it nevertheless complicates utilization, except where fuelwood is so scarce that all woody material is accepted. Elsewhere, the number of trees that are suitable for a specific use and that will reach harvestable size at one time may be too small to cover harvesting costs. If so, silvicultural costs can only be amortized over a longer period. This prospect operates against diversity, favoring instead simplification of stand composition and greater uniformity of stand structure, conceivably at some risk to ecological values.

An aspect of stand diversity often disregarded in silviculture is the vital role of the "consumers" within the ecosystem, particularly the higher forms of animal life. Many game species are eliminated by hunting before silviculture is even considered. However, their potential contribution to pollination, seed dispersal, and control of other forms of animal life could eventually prove crucial to forest productivity. The significance of different components of forest diversity needs study and, meanwhile, managerial deference.

Silvicultural treatment with only present knowledge may do as much harm as good to diversity because the results may not be immediately obvious. Treatment will favor trees thought to best meet future markets or most likely to grow rapidly at the expense of others. Liberation that stimulates growth of selected trees may open stands sufficiently to change composition toward intolerant species. Also, reduced representation of what appear to be potentially useless species, however gradual, may later be found to be ecologically or even economically undesirable.

Heterogeneous secondary forests complicate silviculture for other reasons. Past treatment of these forests generally varies from place to place, from a light cut to remove mature trees of only one species, to clearing, cultivation, overgrazing, and repeated burning. Drastic changes affect the soil quality and may accentuate site variation not apparent in primary forests. The following complications to sustained utilization of tropical moist forests have been suggested (Davidson 1985): species richness; long-lived character of trees; interdependence of plants, animals, and forest dwellers; patchiness of species occurrence; susceptibility to nutrient depletion; and uncertain regeneration.

Cutover forests are generally impoverished in quality as well as quantity because harvesting concentrates on the best species. In certain Philippine forests, the more valuable dipterocarps, which made up more than half the original stands, represented less than 20 percent after harvesting (Caneda 1963, Nastor 1961).

Cutover stands generally contain more timber species than volunteer stands, but they tend to be less uniform as to tree size and canopy continuity. They also may carry a nonproductive overstory. An added variable in such stands is the secondary impact of logging damage, the effects of tree injury being long term as well as immediate. Another uncertainty in cutover forests is the unknown age of the trees that look best for the next crop and its possible significance to their potential. Trees long constrained by suppression, unlike young trees, may be slow to accelerate growth if liberated.

The presence of well-formed trees of marketable species in cutover forests depends heavily on the intensity of prior timber removal and control of logging damage. Concern for the residual stand during logging of tropical forests has been rare, so heavy damage is commonplace. Such losses of future crops can be avoided because many primary moist forests have a large component of trees below harvestable size. Control of logging damage in the Philippines has in large areas saved future crops that are adequate to justify their care for the future (Fox 1967c). If such controls were applied throughout the Tropics, the adequately stocked areas would be extensive. The potential of immature crops within secondary forests is commonly underestimated, because saplings or small poles so widely spaced they are inconspicuous may result in full stocking at maturity.

Trees that remain after cutting, if left untended, may not survive. In one moist forest studied in Sabah, nearly all saplings were smothered by undergrowth 8 years after logging (Anon. 1957a). In a forest in Nigeria, saplings of *Khaya grandifoliola* were reduced from 217 to 22 per hectare during the same period (Anon. 1965c). Even those trees that survive may be of little use because of small size of the species at maturity, poor form, or inferior wood. This is to be expected where logging has removed all of the good trees or has seriously deteriorated or exposed the site.

Volunteer secondary forests commonly are stratified vertically; distinct pioneers are on top and successionally more advanced species beneath. The species of the later stages (beneath) are generally better prospects for traditional timber products. They tend to be straighter and larger at maturity and produce denser and more versatile woods. During the early stages of development, the number of these trees with crop potential may be too small to justify silvicultural treatment, even if some species now considered mediocre are accepted as prospects for the future crop. Yet, the intermediate and subordinate trees down to sapling size may make up a potentially well-stocked forest. Obtaining this forest may warrant immediate or gradual elimination of most of the unwanted overstory, leaving a stand of trees that is relatively uniform in diameter and expected time to maturity.

Silviculture

Silviculture is defined as the theory and practice of controlling the establishment, composition, constitution, and growth of forests (Ford-Robertson 1971). Its practice rests on the natural laws of forest ecology. Although silviculture has a human purpose, management should be the servant of silviculture rather than its master (Schlich 1925). Silvicultural intervention in natural forests may modify the microenvironment, hydrologic cycle, soil properties, and the structure and genetic composition of the forests as well as their growth. With skillful culture, stands that are judiciously modified, even if they differ widely from natural forests, may be more vigorous and productive, as well as free from injury (Smith 1962).

The apparent biological balance of primary forests has long intrigued foresters as a key to sustained yields of usable wood. The attributes of natural forests treated silviculturally to produce timber lie somewhere between those of primary forests and those of intensively managed plantations. Therefore, the culture of secondary forests may not achieve the ideal of ecologists, economists, or even many foresters. Ecologists may see such forests as being of questionable sustainability and as poor substitutes for primary forests as reservoirs of germplasm. Economists may see them as less than competitive with other land uses. Many foresters view natural forests as less productive, at least in the short run, than plantations, despite silvicultural treatment. Results so far tend to support these views.

A fundamental problem faced by silviculturists dealing with natural forests is to determine how "natural" they must be kept to sustain needed environmental values and site productivity given the need to favor the most promising trees at the expense of the others. Much more must be known about natural forests before the consequences of silviculture can be fully understood and predicted in terms of sustainable timber productivity.

Productivity of secondary forests depends ultimately on the effectiveness with which the silviculturist can maintain the site, soil quality, and ecosystem integrity; stock unproductive areas; control competition and growth rates; avoid damage; and harvest products (Poore 1968). Restoration of primary forests would not achieve all these ends. Nevertheless, a cautious approach would be to proceed in the direction of natural succession. Retention of a multistoried, closed canopy should reduce risks (Barnard 1954). Stands could contain more of the preferred timber species, yet also contain a variety of other species in the lower stories to preserve diversity. The result would be a compromise between ecological and economic requirements.

Abandoning the natural stand structure with trees of all sizes growing together in favor of monocyclic practice (one harvest period per rotation) is a departure from nature that has long concerned foresters. The Eighth All-India Silvicultural Conference in 1951 warned that any radical departure from selection fellings (with multiple, light harvests per rotation) gravely risks disturbing delicate ecological balances to the detriment of long-term interests (Rosayro 1952). Whether the structure of unmodified forests must be restored and perpetuated if yields are to be sustainable is still debated (Leslie 1977).

Experience in Sarawak suggests that the highly complex and differentiated structure and composition of primary forests are not essential to maintaining sites and healthy stands (Brunig 1967). Secondary stands with a simpler structure and a higher timber volume did not necessarily imperil ecosystem stability and well-being and, in some cases, were clearly an improvement. Such concerns have never worried the farmer, who grows his crops in the most unnatural way imaginable (Laurie 1941g).

Concern has also long been expressed by foresters for the consequences of treatments that reduce forest diversity. However, the more complex the mixture and the more uneven the canopy, the more difficult is economical timber production (Wilkinson 1960). Blind preference for native species has been questioned, because many do poorly in parts of their natural ranges. Nor is it rational to outlaw exotic species that have been prevented from extending their range solely by barriers other than those of biological adaptability (Peace 1961).

Retention of some natural mixture may be desirable, even at some expense to yield because loss of diversity may affect stability (Odum 1969). Retention of good diversity may also be favored by the potential for markets for more of the existing growing stock. Management may benefit more by intensified processing and marketing of products than by eliminating trees presently unmarketable (Synnott 1979). Experience in the Amazon led to acceptance of common, second-class species that are easy to regenerate (such as *Goupia glabra*) over first-class desirables (such as *Cedrela odorata*) that are difficult to regenerate. The principle is to follow nature, perhaps to guide, but not to dictate (Pitt 1961a).

Silvicultural refinement of forests favors the most promising trees at the expense of others, gradually reducing the representation of other species. Because the ecological consequences are generally unpredictable, a cautious policy would be to retain, at least until their role is more fully understood, little-used species that "look good," and understory trees and opportunists that apparently interfere little with crop production.

Even with these precautions, sustained yield may not result. The favored species may not fully utilize the soil. They may constitute an inadequate nutrient trap. They alone may not support an animal population vital for pollination, seed dispersal, or pest control. Only continuous monitoring can determine sustainability with such departures from nature. Ultimately, even retrenchment could be required.

Agricultural fallows account for large, accessible, and presumably manageable areas that become covered by trees. Cropping/fallow systems will persist where continuous cultivation is not feasible. An untended secondary forest, as a fallow, can restore the soil for recultivation before any trees (except those of extremely rapid growth) become large enough to utilize other than for posts or fuel. Studies in Guatemala and Nigeria have shown that, through fallowing, the organic matter of the soil can be restored to the level of the mature forest in 3 to 10 years (Aweto 1981a, 1981b; Ewel 1981; Machado 1977). Under such circumstances, short-term wood crops of value to rural communities may mature within the fallow cycle.

Application of fertilizers should increase food-crop production, thus reducing pressure on fallow forests and consequent adverse effects on soil and water resources. Under some conditions, fertilizers increase tropical crop yields fivefold at a benefit-to-cost ratio of 3 (Gutschick 1978). Increases in yields due to fertilizers could lengthen fallow periods by reducing the cultivated area, by lengthening the period of food cropping, or both. On favorable sites, fertilizing can even eliminate fallowing, leaving marginal land for continuous food crops. However, because fertilizer must generally be imported, its use is commonly considered politically or economically impractical to the detriment even of experimentation. Despite these disadvantages, crude fertilizer imports into tropical America increased in value between 1987 and 1992 at an annual compounded rate of 16.6 percent (Anon. 1993b). Importing food must cost more than importing the fertilizer to produce it. Food imports into tropical America increased in value at a compounded rate of 12.7 percent from 1987 to 1992 (Anon. 1993b).

Structural Goals. Forest structure is the representation of trees by age, size, crown, or other classes. It is a basic consideration for management for quantity, quality, and continuity of yields. Optimum structure for wood production from secondary forests undoubtedly varies with location and crop. Cutting is generally controlled by stipulating what may be removed rather than what must be left. Commonly, cutting is prescribed in terms of a minimum diameter for trees to be removed, presuming that the next crop will develop from the trees that are left. Residual stand structure is further modified by harvesting damage. The optimum structure the residual forest should have for future productivity is seldom considered when cutting is being planned. Nor are forest managers generally so well financed that they can make a commitment to postlogging treatments that would favor the next crop.

Goals selected for forest structure dictate the degree of uniformity of eventual stands and the severity of cuttings and are thus of ecological as well as silvicultural significance.

Secondary tropical moist forests are irregular in structure. But primary moist forests are so uniform in structure that a single, pan-tropical stand table represents many of them (table 4–7; Dawkins 1959, Leak 1963). Table 4–7 illustrates the "positive" structure of common stands, as shown by the de Liocourt quotient (Sammi 1961) in the final column. If the logarithmic rate of increase in tree numbers constantly increases downward through the d.b.h. range, it would appear that replacement of mortality losses from beneath is uniformly adequate in all tree size classes below a cutting diameter limit of 60 cm. The positive structure illustrated has a larger quotient among the small trees (0.39) than among the large trees (0.17), indicating an apparent abundance of trees in the smaller sizes relative to replacement needs.

The "all-sized" structure suggests that undisturbed tropical forests are also "all-aged," assuming that tree size and age are directly related. However, this assumption is not necessarily true. The fact that most large trees are old does not mean that most small trees are young.

It was recognized early that secondary forests preserve some of the diversity thought critical to the preservation of site productivity (Barnard 1954). A minimum number of tree species was assumed to be all that was necessary to maintain environmental values. More recently, it was recognized that sustained forest productivity requires a balanced nutrient cycle, arising in natural forests from a diversity of forest physiognomies, trophic levels, life forms, and compositions (Brunig and others 1975).

The significance of irregular (all-sized) stocking to forest management has been outlined by Meyer (1956). To manage such forests for sustained yields, a balanced distribution of trees by d.b.h. is necessary. This balance can presumably be expressed by the de Liocourt curve, with a constant quotient of increasing tree numbers in

Table 4-7.—Pantropical stand table for primary moist forests

D.b.h. (cm)	No. of trees per hectare		Logarithm of trees per class	Difference in logarithms
	Per class	Cumulative upward		
10	242.0	431.1	2.38	0.39
20	97.0	189.1	1.99	.39
30	40.0	92.1	1.60	.32
40	19.0	52.1	1.28	.24
50	11.0	33.1	1.04	.21
60	6.8	22.1	.83	.17
70	4.6	15.3	.66	.14
80	3.3	10.7	.52	.16
90	2.3	7.4	.36	.18
100	1.5	5.1	.18	
>100	3.6	3.6		

Source: Dawkins 1959, Leak 1963.

successively smaller d.b.h. classes. Successively harvesting or eliminating trees above a parallel but lower curve and leaving adequate space for growth between cuttings were expected to produce mature timber, liberate immature trees, and foster regeneration while maintaining or attaining the balance needed to sustain yields in the future. This technique was found applicable to *Shorea robusta* forests of India, but a different quotient between adjacent d.b.h. classes was required under different conditions (Mathauda 1960).

A debate between proponents of irregular stocking and converts to uniformity was active in India through the 1930s and 1940s and has not entirely subsided. Irregular stocking has been considered more efficient in that better site use was possible with vertical stratification, leading to more large trees (Bourne 1935). Champion (1936c) agreed with the theoretically greater efficiency but saw no advantage in converting regular forests to irregular ones. He pointed out that teak *(Tectona grandis),* under irregular stocking, becomes poorly formed. He also foresaw reproduction problems. Sagreiya (1941) disagreed with Bourne that in irregular forests more of the basal area can be in large, maturing trees, although he accepted irregularity for dry teak and other understocked areas. He postulated that wood of more even grain is produced in irregular forests.

Laurie (1941b) called for conserving irregular stocking until research could do it justice. He saw advantages such as saving space and harvesting at the right size. He recommended that instead of converting a forest to uniformity, it should be managed as an irregular forest wherever feasible. Davis (1941) summed up the debate at that time by indicating that the best course is flexibility, with uniformity a consideration only where stocking is adequate to provide a choice.

Managing large areas of natural forests with irregular stocking continued over a long period. The system in vogue in what is now Sri Lanka in 1955 used a diameter limit of 50 cm with a felling cycle of 10 years (Rosayro

1955). Tending (weeding of saplings and liberation of poles) was done to rebuild the growing stock. In Ghana, 12 years of tests with uniform systems showed that they were not universally applicable (Foggie 1957). The conclusion was that irregular forest management was best. Ten years later, irregular stocking was still considered suited where highly desirable species are present. The technique operated on a 20- to 30-year felling cycle, with a midcycle of thinning (Osafo 1970). Irregular management schemes have been used extensively in parts of Malaysia, Nigeria, and Queensland, Australia, and on a small scale in Trinidad and Puerto Rico (Baur 1964a).

Foresters in India in 1959 were practicing a form of selection management. Generally, they used diameter-limit control on 20- to 30-year cycles, but intensities of tending varied widely (Stracey 1959). By avoiding heavy fellings, they thought they would preserve the character of the forest. This, Stracey said, was a widespread misconception. He concluded that using "selection" for harvest cuttings followed by felling and girdling to establish regeneration—the common procedure—tended to produce an even-aged forest. Stracey recommended carefully controlled tendings, conservation of some less valuable species, concentration on shade-bearers (tolerant species), and a longer transition period of conversion.

Preserving natural stand structure presents practical problems as difficult as those of maintaining the natural composition. A major argument for saving secondary forests is that they contain immature trees with economic potential. These trees may range in size from seedlings to trees nearly mature. Efforts to produce economical crops of large trees from such stands have not yet been generally successful; therefore, conversion to forests of uniform tree sizes, regardless of the sacrifice of larger and smaller trees, became the general practice.

Management systems retaining irregular forest structure by several partial cuttings during a rotation, termed "polycyclic," resulted in cumulative logging damage that was considered unavoidable and intolerable in Uganda and Nigeria (Dawkins 1961b). Also, the continuous overstory was said to so suppress potential crop trees during their early years that they were incapable of growth acceleration later. An added drawback was the high unit cost of harvesting the small volumes yielded per unit of forest area from partial cuttings (Philip 1962).

Repeated partial fellings have been criticized on another count. In all forests, the large trees, whether or not they are older than the others, are obviously successful, and thus may be genotypically superior to others. The removal of these large trees with each cut may leave trees genetically inferior for future crops and seed sources (Ranganathan 1951). This dysgenic trend, if it exists, was seen as progressive (Palmer 1975). In volunteer secondary forests composed of trees that may have all become established at about the same time, harvesting only the largest may accentuate this effect.

Vanniere (1975) recommended converting to monocyclic management in stands where the immature trees make up a small fraction of the volume before harvesting. Palmer (1975) questioned the degree to which logging damage can or will be reduced. His view is supported by observations in Malaysia where even after tree markers indicated the felling direction for each tree, little effective control was exercised (Tang and Wadley 1976a, 1976b).

Dawkins (1958b, 1958e, 1961b), on the basis of personal study in Uganda and widespread observations elsewhere, questioned polycyclic management of irregularly stocked tropical forests as a continuing source of export-size timber. He concluded that a number of constraints limit the potential of irregularly structured forests. These are as follows:

- Cuttings must be repeated at intervals shorter than the difference between the rotation for the oldest trees to be produced and that of the youngest merchantable trees. This constraint limits yield per cutting.

- The cycle must be less than 30 (and preferably less than 20) years to avoid premature removal of still-growing stems.

- The cycle must be long enough to produce an economically extractable volume. When the previous constraint is also taken into consideration, this constraint calls for fast growth. Very few natural high forests grow desirable species faster than 0.4 m^3/ha/yr.

- The crop tree species must be shadebearers and able to expand an initially stunted crown after decades of suppression. (Fast-growing trees of Uganda are capable of neither.)

- To produce 3.5 m^3/ha/yr, at least 10 trees must be removed per hectare every 10 years. Such a harvest will destroy or damage 20 to 25 percent of the adolescent and pole stock. Saplings may have to survive five such cuts to reach maturity, an unlikely prospect.

- Longer cycles mean heavier cuts and even fewer trees for replacements. With shorter cycles, there is less prospect that the damaged areas will overlap.

- The stand table must be strongly positive, with an abundance of saplings entering from below.

Dawkins (1959) further concluded that the large crown-diameter-to-d.b.h. ratio required for rapid growth of tropical trees (>20) calls for early crown growth and, therefore, a lack of suppression. His records indicated that a d.b.h. of 60 cm may be attained in 30 to 90 years and 80 cm in 40 to 120 years, the faster growth occurring in stands of 18 m^2/ha of basal area or less, and the slower with 25 m^2/ha or more. However, growing beneath or alongside trees of an older generation, no African tree is capable of reaching 80 cm in less than 80 years. Thus, unless rotations can be reduced to 40 to 50 years or logging damage to much less than 0.01 ha per tree felled, Dawkins (1958b) foresaw no prospect for sustainable yields of export-size timbers of more than 1.4 m^3/ha/yr. Yields might, nevertheless, be more than doubled where there is a market for intermediate-size trees, he concluded.

These constraints led Dawkins to encourage monocyclic systems where neither the problems of felling damage nor of early suppression impinges on productivity. A positive stand curve is still required. Yields as high as 4.3 m^3/ha/yr were seen as possible under good management and favorable markets.

Nicholson (1965b) questioned Dawkins' conclusion that long-suppressed trees are moribund. He presented data from Sabah showing that growth accelerated 1 year after logging (table 4–8) and added that growth was still increasing at the time of measurement.

Polycyclic (Selection) Practice. As fundamental as Dawkins' reasoning may seem, it has not settled the stocking issue. Some continue to favor irregular stocking as ecologically conservative. Others question the general applicability of the Ugandan findings. But no evidence has come to light that challenges the modest yields Dawkins predicted, except better markets for smaller trees, something that he foresaw.

Table 4–8.—Growth acceleration after logging in Sabah (cm)

D.b.h. class	Mean annual diameter growth: Before logging	1 yr after logging
5–15	0.28	0.87
15–25	0.46	1.26
25–35	0.49	1.46
35–45	0.53	0.70
45–55	0.52	1.20

Source: Nicholson 1965b.

The experience in Uganda of conversion from irregular to uniform stocking brought to light a number of concerns (Philip 1962), including the following:

- Diagnostic sampling, revealing not only the number of future crop trees but their silvicultural needs, is required for designing treatments of cutover stands. To avoid the impediment of logging slash, such sampling should precede felling.

- Prediction of the effects of different logging intensities on the residual forest is difficult.

- Ordering of the "coupes" (annual compartments) must be related to the dates at which their stands mature. The cutting rate must be adjusted during conversion to avoid breaks in harvesting yet ensure an orderly second rotation.

- Because regeneration is extremely variable from place to place, tending operations must be sensitive to differences from one coupe to another.

Stracey and Saikia (1960) favored selection in Assam, India, to avoid sacrificing good immature trees in converting to uniform stands. They advocated that a third of the currently noncommercial tree species should be saved because they may become useful. Schulz (1967) hesitated to convert to a monocyclic system in Suriname, apparently for the same reason. On the other hand, Sabharwal (1941) had earlier pointed out that, in converting from irregular to uniform structure, all the advanced growth need not be sacrificed if some irregularity is acceptable.

Selection management of the mora *(Mora excelsa)* forest of Trinidad has been recommended after removal of overmature, unsound, and defective trees (Bell 1971). Removal of five to eight trees per hectare was proposed on 10- to 15-year cycles after the initial treatment. Felling all trees down to 58 cm in d.b.h. left 107 undamaged or slightly damaged trees per hectare of 10 cm in d.b.h. or more (a residual basal area of 3.4 m^2/ha). Felling of 12 evenly spaced, large trees per hectare left 159 undamaged or slightly damaged trees per hectare (a residual basal area of 12.4 m^2/ha).

Under some conditions, the amount of logging damage does not itself preclude a polycyclic system (Redhead 1960a). For example, crawler tractors may do almost twice as much damage as felling, but the damage can be reduced by avoiding groups of advanced growth so that enough trees of 20 cm in d.b.h. or more remain to make a second crop as good as the first. Observations in Ghana (Mooney 1963) also suggested that felling damage need not be as great as Dawkins concluded.

In Philippine dipterocarp forests, marking of needed immature trees before the harvest kept tractor damage within tolerable limits even though far more trees were removed than in Uganda (Fox 1967a, Tagudar and Quintana 1957). Marking selected crop trees before logging has also been prescribed in Indonesia (Soerianegara 1970). Developments in yarding partial cuttings in the Temperate Zone suggest that logging damage in the Tropics might be significantly reduced with overhead removal systems such as skylines (Wendel and Kochenderfer 1978).

Baur (1964b) generally accepted Dawkins' conclusions concerning selection forests, referring to the repeated logging damage, high yields required by mechanized logging, and their unsuitability for light demanders. He also pointed out some disadvantages of converting to uniform stand structure: the loss of small healthy stems and possibly also species as well as greater soil exposure after complete harvests.

Dawkins convinced forestry officials in Uganda to convert to uniformity but with the understanding that it would not soon produce crops that are either even sized or even aged (Dawkins 1958g). Thus, reverting to selection could still take place if needed. However, only under uniform structure did Dawkins expect to bring a sufficient crop of unscathed juveniles to maturity. Conversion to uniform structure as visualized by Dawkins could begin with a salvage cut in which the minimum profitable harvest is less than the total stand.

Palmer (1975), like Dawkins, concluded that the prospects for low final yields and small growth increases as a result of silvicultural treatment make investments in silviculture in irregular forests unattractive. He held out one hope that Dawkins also recognized: Over time, keeping the basal area below two-thirds of the maximum might substantially increase growth. This would require repeated thinnings, but where markets for the products exist, they might be profitable.

In the Temperate Zone, Bormann and Likens (1981) concluded that a number of environmental constraints should be applied to any production system (such as uniformity) calling for clearcutting: (1) utilize only sites with strong regenerative capacity, avoiding steep slopes and shallow soils; (2) leave uncut strips on both banks of stream channels; (3) limit the size of cuttings to several hectares to ensure peripheral seed sources and minimize losses of dissolved nutrients and eroded material; (4) select a rotation long enough to permit the system to regain nutrients and organic matter lost by extraction and site exposure from clearcutting; and (5) respect postcutting recovery species, even if they are not ultimately marketable.

Heavy monocyclic cuts will periodically interrupt nutrient conservation because large volumes of logging slash will be decomposing at a time when the remaining network of live roots is incomplete. With survival of an adequate natural understory or prompt natural regeneration, this period of imbalance may be short. However, more needs to be known about the magnitude and duration of nutrient losses as affected by different harvesting intensities and treatments of slash.

What does all this mean in terms of structural goals for secondary forests? Many of the experiences reported begin with primary forests having a wide range of tree sizes and dense overstories with high tree crowns. In favored circumstances, enough adolescents 20 cm in d.b.h. or more may be left for a second crop long before newly regenerated trees could mature. Young stands that contain potential crop trees of uniform size suggest maintenance of uniformity. Late secondary forests with a wider range of diameters may offer either option, uniformity or irregular stand structure. In typical secondary forests, some of the problems that concerned Dawkins (1961c) may be less serious. Felling damage should be much less, because there are few or no large trees. The lighter cuts implicit in polycyclic systems may prove more practical in view of the rapid growth of local demand for wood and the greater accessibility of secondary forests. Additional species may enter this local market, increasing the proportion of marketable trees and raising yields correspondingly.

Obviously, silvicultural treatment must consider both the composition and the structure of the forest. But the decision on structure may be postponed. With typical unmanaged secondary forests, the first step may be to improve composition rather than to select potential crop trees. As time passes and as the potential of natural regeneration, the marketability of more tree species, and the economics of intermediate cuttings become more predictable, the basis for a decision on forest structure for crop production should become clearer.

Diameter Limits. Given the natural structure of mixed tropical forests and the assumption, albeit generally unproven, that mature trees cover a younger understory waiting to be released, foresters have presumed that the selection system should be appropriate. Under such luxuriant growth, this system presumably would call only for harvesting the mature trees, liberating those suppressed, and fostering regeneration where needed. Because selection felling preserves a wide array of diameters, this method has been considered unobjectionable. It certainly seems more judicious than alternatives calling for drastic modification or sacrifice of forests before their dynamics and potentials are fully understood.

Past study of the structure of natural tropical forests has led to the supposition that repeated removal of mature trees should stimulate adequate replenishment from beneath. An almost universal practice has been the application of minimum diameter limits in timber exploitation to preserve the immature trees so that they can be available for later harvests. An additional assumption was that repeated cuttings of this kind would preserve the natural forest structure and, therefore, would perpetuate production. In the absence of knowledge of, or financial resources for, more intensive systems, this practice leaves open the options for more refined silviculture in the future. Therefore, diameter limits may be a defensible, interim, harvesting guide. Even if the residual stand is later replaced, the site and trees are as well protected as possible with current supervision.

It became apparent long ago that diameter-limit cuttings in tropical moist forests did not ensure high productivity of future timber crops. Alone, they do not protect immature trees from damage that results from harvesting. They fail to balance the growing stock or thin the smaller trees (Trevor 1923). Nor do they offer any promise of sustained yields. Nevertheless, diameter limits and subsequent selection cutting of teak forests in India were recommended because financial resources were insufficient to fell and replant these forests. The residual forests, even if less productive than plantations, provided a buffer against human trespass.

Shelterwood. Forests composed of trees of about the same stem diameters have been referred to here as "uniform." Silvicultural systems leading to uniformity include shelterwood, in which an overstory is removed during a brief period, and clearcutting, which subjects the future crop to full sunlight from the outset. Cutting takes place only during one part of the rotation, so such systems are termed "monocyclic." All trees mature and are harvested at about the same time.

Simplicity is the great advantage of these systems. Compartments are treated in sequence, producing a series of age classes, preferably as many as there are years in the rotation. Regulation of the rate of harvest may be either by forest area or by timber volume.

A disadvantage in converting secondary forests to this structure is that trees in the crop to be harvested must mature at about the same time, a condition that many secondary forests do not meet. Trees too large or too small to mature in synchrony with the harvest may have to be sacrificed. Application of this conversion in Uganda required removal at the outset of all "weed" trees down to 10 cm in d.b.h. (Earl 1968).

By 1932, a modification of the European shelterwood silvicultural system, termed "tropical shelterwood," was in use in what is now Malaysia (Hodgson 1932). Its main objectives were to remove all mature timber in one or more fellings within a short period (usually less than 10 percent of the rotation) and to apply ancillary silvicultural treatments to stimulate regeneration of a new crop of relatively uniform age or tree size.

Tropical shelterwood resulted from a number of widespread conditions. The naturally low merchantable volumes of marketable trees made it financially necessary to remove nearly all of them at once. Consequently, only small trees of the better species were left. These, to prosper, needed more light than is available beneath typical residual overstory (Baur 1964b).

Shelterwood cutting has been superior to systems that maximize present harvest and leave future crops to chance. Indeed, shelterwood has favored the next crop in felling practice, canopy manipulation, seedbed preparation, and control of vines and weeds. It has also tended to protect the soil and existing saplings of desirable species.

Shelterwood does have its restrictions: (1) regeneration of a new crop of the desired species must be either advanced or obtainable promptly after cutting; where unmerchantable species make up much of the forest, such regeneration may be rare; (2) regeneration of the fast-growing species may require almost full sunlight rather than overhead shelter; and (3) any second or final harvesting of the overwood must be done through the new crop, with inevitable damage.

Regeneration of select species following shelterwood cuttings has required a host of silvicultural treatments, including climber (vine) cutting, canopy openings, understory removal, burning, soil scarification, liberation, thinning of advance regeneration, and even supplementary artificial regeneration (Baur 1964a).

Tropical shelterwood, at best, has proved acceptable. Because as few as 75 stems per hectare may be sufficient to produce a fully stocked crop of export timber, adequate regeneration already may be present or quick to appear. The presence of early shade is believed to increase the diversity of regeneration. With canopy manipulation, growth of the next crop may be accelerated. Yields from secondary forests receiving no cultural treatment may average no more than 2 m^3/ha/yr; yet, shelterwood yields on the best sites might reach 7 m^3/ha/yr and increase still further if uses are found for thinnings (Baur 1964a). These yields are clearly below the maximums for plantations, but the latter may not repay establishment costs on sites that would otherwise regenerate naturally.

Tropical shelterwood has seen limited success. In Nigeria (where markets have long been favorable), the practice began in primary forests with a pole felling (Hodgson 1932). This was followed by a seed felling that opened the overstory but left seed bearers believed capable of inducing regeneration. After 2 or 3 years, a low-level cleaning was done, followed by a second seed felling in the 4th year. In the 6th or 7th year a second cleaning was made, followed by the final felling if regeneration was then adequate. Cleanings followed thereafter as necessary.

Tropical shelterwood in what is now Malaysia, despite repeated tests, proved unreliable. The irregularity of seed years played havoc with scheduling. Fellings had to be scheduled around seed years, because the intolerants could survive only 2 to 3 years without release (Durant 1936). For tolerant species, cleanings had to be scheduled to stimulate growth before fellings. A uniform system was substituted in Malaysian lowland forests to exploit the capacity of some of the light-demanding dipterocarps to escape climber growth under full sunlight.

Despite the problems with tropical shelterwood in what is now Malaysia and growing disenchantment generally with natural regeneration techniques in India (Ranganathan 1951), a Malayan forester reintroduced the system into Nigeria in 1943, proposing to concentrate on regenerating *Triplochiton* (Mutch 1949). An earlier uniform system, attempted in 1927, failed for what was believed to be a lack of adequate light control (Lancaster 1961b). The objective of the new system was to convert mature natural forests into a series of relatively even-aged coupes in one rotation (Onyeagocha 1962). Climber cutting, done well before exploitation, was followed by poisoning of unwanted trees of intermediate size, leaving the overstory untouched. Cleanings followed harvesting of the mature timber by 1, 3, 8, and 13 years.

Although the initial treatments were not successful, reportedly because of inadequate seed bearers and ineffectual poisoning, more than 25,000 ha were under treatment by 1948 (Anon. 1949d). Seedling counts of 150 to 200 per hectare, well over the accepted minimum of 100 per hectare, were encouraging, and suggested that the number of seedlings had doubled. Some well-illuminated seedlings also doubled their height in 1 year (Anon. 1949d). Providing enough light to encourage regeneration but not weeds was a problem. Light insufficient for *Terminalia* and *Triplochiton* but adequate for shade-tolerant Meliaceae had become the goal (Mutch 1949). After the final felling in Dahomey, now

Benin, 53 of 55 ha contained more than 500 saplings per hectare 3 m tall or more, and 27 ha had 1,000 or more saplings.

In Nigeria, leaving understory trees was considered necessary to control vine growth (Anon. 1957d). Yet, poison-girdling was needed to keep the canopy open enough to encourage sapling growth. A study of a shelterwood forest at Sapoba, Nigeria, showed that the cost of poisoning must be considered in selecting liberation practices (Henry 1957). The elimination of all trees of no economic value 58 cm in d.b.h. or more took 10 trees per hectare. Removal of trees overtopping economically valuable saplings and poles took 114 per hectare. Removal of all trees 10 cm or more took 273 per hectare.

A Nigerian technique, as revised in 1954, may represent the maximum development of a tropical shelterwood system. It consisted of the following operations (Anon. 1955a):

- Year 1—Demarcate grid lines.
- Year 1—Cut within 15 cm of soil climbers, herbs, shrubs, and trees of no economic value and deformed trees of desirable species.
- Year 2—Conduct prepoisoning cleaning. Cut back new creepers and maintain condition of previous operation.
- Year 2 (and possibly year 4)—Count regeneration and enumerate pole crop.
- Year 2—Perform seedling poisoning. Work up canopy from below by eliminating lower trees to encourage existing reproduction and to strengthen new regeneration if fewer than 100 trees per hectare.
- Year 2 or 4—Perform clearance poisoning. If regeneration yields fewer than 100 trees per hectare in year 2, poison all shade-casting, noncommercial trees of lower and middle stories, leaving only those that are straight and have small crowns.
- Year 3 to 5—Perform postpoisoning cleaning to about knee height.
- Year 3 to 5—Free established seedlings and saplings.
- Year 6—Exploit (harvest) and repair damage.
- Year 7—Remove shelterwood, including all noncommercial trees interfering in any way with the new crop.
- After year 7—Dibble in trees if fewer than 100 trees per hectare.
- After year 7—Line plant if needed.

Climber cutting was continued as long after shelterwood removal as necessary, in rainy seasons of the 9th, 14th, and 17th years (Okon 1962). The provision for dibbling and line planting suggests that natural regeneration may be only partially successful. One postexploitation stand of reproduction averaged 210 trees per hectare, then considered inadequate (Lancaster 1961a). Much doubt arose concerning the technique. Nevertheless, under favorable circumstances, seedling, sapling, and pole counts in Dahomey, now Benin, seem to have been adequate (table 4–9; Onyeagocha 1962).

By 1970, the Nigerian experience had led to disenchantment with tropical shelterwood (Baur 1964a, Oseni and Abayomi 1970). It began with failures in postlogging gaps, followed by difficulties of synchrony with seedfall, and finally, necessity for continued release. The main effect has been to release regrowth already present rather than to induce new regeneration. The stands produced were not of even-sized trees (such

Table 4–9.—Shelterwood crop production in Dahomey (Benin) and Nigeria

Tree size		No. of trees per hectare	
Height (m)	D.b.h. (cm)	Before pretreatment (1952)	After exploitation (1957)
0–1	—[a]	6	74
1–3	—[a]	19	62
3–10		44	71
—[a]	10–50	48	48
Total		**117**	**255**

Source: Onyeagocha 1962.
[a]Not measured.

as in a plantation) because of different growth rates within and among species. The fastest growing trees were maturing in half the time required for the slowest! Even where tropical shelterwood succeeded in bringing on a new crop, noncommercial trees comprised more than half the stands, requiring continued freeing in order to make the site produce to capacity. The composition of the forest shifted from upperstory to middle-story species, and the light demanders generally failed (Lawton 1976).

Lowe (1984) pointed out in his "obituary" to tropical shelterwood in Nigeria that the practice was intended to supply mainly the export markets from stands where only natural regeneration was considered possible because of limited funds. The system failed to reconcile the need to open the canopy and at the same time control growth of climbers and herbaceous weeds. It was complex to apply and difficult to assess. Yet, canopy opening appeared to double the amount of regeneration, and climber cutting doubled the number of potential final crop trees. Nevertheless, tropical shelterwood was abandoned in Nigeria, not because of technical deficiencies but because shelterwood forests, however successful technically, did not compete with cocoa or other alternative crops for which the land was considered better suited. Also, pressures for wood forced a reduction in the rotation from 100 to 50 years. Lowe concluded that, at the then-current rate of conversion to timber plantations, it was unlikely that there was sufficient time for a naturally established seedling to reach merchantable size before the forest would have to be converted to a timber plantation or some agricultural use.

Extensive experience in what is now Ghana, with tropical shelterwood, beginning in 1947, showed that shelterwood required two conditions: a normal forest and a reasonable number of seed bearers (Taylor 1954). These conditions were not common to large areas. The system proved difficult in overmature forests, pole stands, or old secondary forests with poor seed sources. Even the presence of mother trees did not ensure success (Foggie 1957), although an early test in the Bobiri Forest yielded 490 trees of 4 cm in d.b.h. per hectare of 13 valuable species (Lane 1961).

The complexity of treatment in Ghana is illustrated by practices in the Bobiri Forest (Osafo 1968a). One compartment went through 19 years of shelterwood treatments. These included three canopy reductions, 6, 5, and 4 years before felling; regeneration assessments carried out 3, 2, and 1 year before felling and every third year thereafter; cleanings 2 years before and after felling; climber cuttings 1, 9, 11, and 12 years after felling; and poisoning of residuals 4, 5, 6, 8, and 11 years after felling. Damage from the removal of the overwood was generally excessive. Under any shade density chosen, the trees of commercial species were outgrown by weeds.

Mooney (1962, 1963) concluded that, if quality timber was the goal, the results to 1962 in Ghana ranged from excellent to hopeless. He foresaw difficulties in bringing quality species through fast-growers after the stand is opened. When the overstory is removed, light-demanders invade, requiring repeated thinnings to preserve the export species. As an alternative, he recommended abandoning the export species for the light demanders. Many of these have since become readily marketable.

An allied technique in the Congo, termed "uniformization par le haut," began with enumeration and treatments to increase uniformity before harvesting (Baur 1964a). Useless overstory trees were eliminated, and the range of size classes was reduced by selective poisoning. Light intensity at the ground level was increased to 30 to 40 percent of full daylight. Under favorable conditions, climbers were not a serious problem.

In the Western Hemisphere, the outstanding example of a tropical shelterwood system is that which apparently is extant in the Arena and McNair Ravine Sable Forest Reserves in Trinidad, where the work began about 1935 (Baur 1964a). Early observations had concluded that plantations of species such as *Calophyllum brasiliense, Carapa guianensis,* and *Vitex divaricata* did poorly on sandy soils (Ayliffe 1952, Brooks 1941b). In contrast, natural regeneration under shelterwood on sandy soils had proved adequate. Nine species in Arena and 18 in McNair, including species of *Byrsonima, Hieronyma, Nectandra, Schefflera, Tabebuia,* and *Terminalia,* were accepted as potentially marketable. Tendings (including climber cutting and cleaning of undergrowth) were followed by gradual removal of shelterwood for the next 3 or more years. The best overstory trees were left, but the understory trees were removed, after which the remaining overstory was thinned to provide adequate light (Moore 1957). Charcoal-burner labor has been used for much of the work. At Arena, a 50-year rotation to 50 cm in d.b.h. has been contemplated for the rapid growers, and 60 years for others, to be left as standards (Raets 1963). A yield of about 5 m^3/ha/yr was expected (Ayliffe 1952).

In summary, it is clear that a strong effort was made to apply tropical shelterwood in many countries. The record suggests that it was generally a failure. Most discouraging were the impressions at many locations that where it "produced" a new crop, the crop was already on the ground and, elsewhere, that it failed to induce new regeneration of the export timber species of the day. Less has been said about the labor costs, which became prohibitive as wages rose. The concept, however, may again be worthy of trial, now that many former weed species are marketable. The advantages of monocyclic management with preservation of a continuous canopy and much of the natural diversity are now assessed more highly than in the past.

Clearcutting. Clearcutting of tropical forests to harvest industrial timber (as opposed to fuelwood) is almost unknown because most trees of mixed forests have not been marketable. Nor is clearcutting of such stands a priori a logical option for the silviculturist. Immature trees of valuable native species come up naturally through at least partial shade. Successful regeneration of desirable species after clearcutting is a rarity.

The most notable and possibly a unique example of successful heavy cutting for regenerating moist tropical forests for the production of large trees is in Peninsular Malaysia where, after the Second World War, logging became mechanized (Baur 1964a). Early improvement cuttings had shown that regeneration was usually already present. A single heavy felling, leaving no seed trees, was then proposed, counting on advanced regeneration. This proposal marked the beginning of the Malayan Uniform System (Baur 1964a), which depended on: (1) adequate stocking of seedlings of useful species at the time of exploitation, (2) complete removal of the canopy, (3) no tending until access was clear beneath the regrowth, and (4) prevention of redevelopment of climbers.

Regeneration averaging one seedling up to 2 m tall in 40 percent of the 2.5-m^2 plots was considered adequate. If this level was not met, a seed year was awaited. Felling was done within 2 years thereafter and was followed by poisoning all useless stems down to 5 cm in d.b.h. From 3 to 5 years later, sampling indicated the need for climber cutting or followup poisoning. Experience and improved markets later led to less stringent requirements: 30 percent stocking became accepted as adequate, and up to 20 percent of the selected seedlings could be in the light wood classes (Baur 1964a). A later shift in land use, relegating forest production to the uplands where natural regeneration was less plentiful, led to the conclusion that future wood supplies in the area must ultimately rely chiefly on artificial regeneration.

In Nigeria, four methods of converting cutover forests to new crops were tried, beginning in 1927. The first, cutting all but 10 seed trees per hectare and burning, apparently failed, because it produced a climber tangle (Baur 1964a). A second system, leaving overstory groups to bear seeds and cutting and burning the lower stories and climbers, proved more successful but called for more supervision than was available. A third system, calling for planting openings (enrichment), proved too dispersed to administer. A fourth, a uniform system, involved a gradual opening by climber cuttings and girdling undesirables about 3 years before logging. It was successful in that the increased light stimulated existing natural regeneration (Baur 1964a). Nevertheless, gap planting was sometimes required.

Preharvesting Treatments. Failures in natural regeneration have generally been ascribed to an absence of advance seedlings, a lack of seeds due to harvesting of seed bearers of the desired species, logging damage, and the smothering effect of subsequent vines and weeds. These conclusions have led to efforts to promote natural regeneration in mature forests before harvesting.

Experience in India has produced varied results. Fellings in the understory do not induce regeneration but may help an existing crop (Champion 1936b). Indian dipterocarps reportedly need bare soil for germination and gradual liberation thereafter (Sen Gupta 1939). Removing undergrowth and working soil just after seedfall encouraged natural regeneration but mostly of noncommercial species (Iyppu 1960). Until the sapling stage, weedings were required three times per year.

In what is now Malaysia, it was concluded early that overstory fellings do not induce new crops of dipterocarps. Instead, openings in the canopy in advance of regeneration produced a dense understory, jeopardizing any desirable seedlings that might have appeared (Watson 1936). In the dipterocarp forests of the Andaman Islands, reducing the density of the canopy at different heights and burning the debris before seedfall reportedly brought in good regeneration but also weeds (Pooraiah 1957).

African experience with preharvest inducement has been more encouraging. Intensive treatment of small areas has produced some spectacular results. In Nigerian studies, manipulating seedfall and light conditions and cleaning around seed trees led to local successes with many species (Kennedy 1935, Paul 1953). The standard regeneration treatment from 1932 to 1935 included understory clearing around one seed bearer of economically valuable species for each 2 ha (Paul 1953). Clearings were as large as 0.8 ha, and debris was burned before seedfall. Regeneration, where copious, was thinned to a 1- by 1-m spacing. Secondary species were allowed to remain where needed for shade. But the labor cost was about 200 days per hectare (d/ha).

Cultivation beneath seed bearers of *Maesopsis eminii* produced abundant regeneration in Uganda (Swabey 1954), as it did for *Callitris calcareta, C. robusta,* and *Cupressus lusitanica,* in Nyasaland, now Malawi (Anon. 1952f), and for *Flindersia brayleyana* and *Toona ciliata* in tropical Australia (Anon. 1958g).

Larger scale treatments in Africa, however, have been less convincing. Between 1944 and 1948, light poisonings and cleanings were done in Nigeria during each of the 5 years in advance of harvest (Jones 1950). As many as 200 seedlings per hectare were found in some areas, double the minimum standard. An opinion persisted, however, that much of this regeneration was present before silvicultural treatment (Onyeagocha 1962). This belief seemed supported by the fact that gaps in the regeneration, when cleared, did not regenerate but instead came up in weeds. The 5-year advance period before felling exposed larger saplings to logging damage. In one study, the larger saplings were found more vulnerable to felling damage than smaller ones (Jones 1950), but in another study they were considered better able to withstand logging than seedlings (Ellis 1951). The lack of widespread success of these treatments has been laid to irregular fruiting, a lack of seed bearers (as few as one per hectare), and differences in shade requirements for each species (Catinot 1974).

In America, few observations of the results of preharvesting treatments have been recorded. *Cedrela odorata* regeneration was found to be abundant on a farmed area adjacent to a forest in what is now Belize (Anon. 1949a). In the Amazon, an experiment in a secondary forest compared three intensities of opening: (1) cutting back noncommercial saplings of less than 5 cm in d.b.h., (2) the same as (1) plus poisoning some understory trees, and (3) the same as (2) plus killing some of the larger trees (Pitt 1961b). Fifteen native species were considered marketable. By the end of the first year, regeneration in the light treatment rose from 18 to 60 percent of full stocking. In the second treatment, regeneration rose from 37 to 89 percent, and in the third treatment, from 20 to 100 percent. It was concluded that basal area must be reduced to 15 m^2/ha for trees of 10 cm in d.b.h. or more (10 m^2/ha for trees 25 cm or more) to induce regeneration.

Elimination of Relics. Relics are large trees that remain singly or in groups well above cutover forests. Some may have been left for seeds, but most lacked a market. Their survival is uncertain, their growth is of little moment, and they may create unwanted shade or fall onto the future crop.

Experience in handling these relics is mostly from countries in the Eastern Hemisphere. In what is now Malaysia, Watson (1936) disproved any need for heavy initial shade for dipterocarp saplings, showing that rapid growers can come through in large openings. He recommended early felling of seed bearers to avoid greater damage later. His observation that the meranti group of Dipterocarps (desirable light woods) respond vigorously to full light convinced him that, where regeneration is adequate, the canopy should be removed as rapidly as considered safe. He saw removing the canopy in one operation as both economical and effective. He considered removing the upper canopy alone to be of benefit only to the lower canopy, not to regeneration. Watson's conclusions were confirmed 10 years later by the Malayan Uniform System. By 1950, the standard practice in lowland dipterocarps with advance regeneration was complete harvesting in one operation and poisoning of useless stems as felling progressed (Barnard 1950a).

Early reports from Sabah led to the same conclusion: If adequate seedlings are on the ground before logging, all noncommercial trees should be poisoned soon thereafter (fig. 4–6; Nicholson 1958b). At that time, it was unclear whether some commercial overstory should be left for an interim harvest before the seedlings matured.

Later studies in Malaysia supported leaving large seed trees that were healthy and had good crowns (Wyatt-Smith 1963). It was expected that they would be fast

Figure 4–6.—*Elimination of a relic in Sarawak, using frill-girdling and an arboricide.*

growing and would continue to grow well if retained. Later removal of such trees was seen as a potentially profitable, intermediate cutting. Measurements in one such felling indicated that harvesting these trees would not unduly harm the future crop if logging were carefully controlled (Wyatt-Smith 1963). However, if such a felling is imminent, tending of the young growth should be postponed until logging has been completed (Wyatt-Smith and Vincent 1962b).

Other studies in lowland dipterocarp forests indicated that relics did not contribute to future production (Wong 1966b). In one forest, 15 of 74 relics died within 7 years, and in another, from 6 to 28 percent of the *merantis* died within 10 years. By 1970, the standard Malayan Uniform System practice with dipterocarps was harvesting down to 40 to 50 cm in d.b.h., in one or two stages 7 years apart, and girdling down to 30 (or even 10) cm in d.b.h. (Burgess 1970).

Treating relic stands has been considered the most important silvicultural operation in the Malayan Uniform System (Tang and Wadley 1976b). Reduction of the overstory to 25 m^2 of basal area per hectare is important to the development of regeneration. Further reduction is much less so. With a relatively tolerant new crop, elimination of the relic stand may be delayed up to 4-1/2 years. If relics must eventually be girdled, however, it is advantageous to do so immediately.

Removing relics as well as other unwanted trees in secondary forests requires the use of safe, effective, and inexpensive techniques. Felling was discontinued years ago because of the cost and the damage to residual trees done by live crowns (after which, climbers were a problem). Girdling is much less costly than felling, but the death of the tree may be neither prompt nor certain. Moreover, girdling is difficult on trees with fluted boles, and if incomplete, the tree may persist indefinitely. Girdled trees generally do not die immediately anyway, so the benefits are slow to appear. This is a sound argument for the use of arboricides. Whether girdled or poisoned, trees normally lose their crowns and otherwise deteriorate before falling, reducing the impact on trees below.

Natural Regeneration. The term "natural regeneration" means renewal by self-sown seeds or vegetative means (Ford-Robertson 1971). There has been much confusion in the past between inducement of new seedlings and stimulation of seedlings already present. The distinction is important because inducement has generally proved much more difficult than stimulation. The two have commonly been confused where the abundance of a seedling crop was not reliably determined before treatment was begun. Many of the greatest successes reported in natural regeneration are where the new trees appeared before any treatments (Paul 1953).

Tropical moist forest sites have remarkable recuperative powers and rapidly revegetate disturbed areas or openings (figs. 4–7, 4–8). In strictly quantitative terms, natural regeneration in the region is seldom much of a problem

Figure 4–7.—*Complete regeneration of* Pinus occidentalis *after heavy logging in the uplands of Haiti.*

Figure 4–8.—*Abundant regeneration released by liberation of a crop tree (center) 10 years earlier.*

Figure 4–9.—*Twenty-four-year-old volunteer secondary forest development in the Philippines.*

except where deforestation is so extensive or lasting that root systems and nearby seed sources are destroyed (fig. 4–9). However, an adequate crop of naturally regenerated seedlings of desirable species is not awaiting the forester in most volunteer tropical forests. Regenerating only those tree species that are potentially marketable for export calls for something distinct from ordinary natural forest succession. Several difficulties have confounded efforts to naturally regenerate these selected species (Banerji 1958, Wadsworth 1962): (1) commercial harvesting deteriorates the forest's potential to produce seeds of marketable species; (2) harvesting leaves both openings and untouched areas, neither of which may be ideal for regenerating desired species; (3) good seed years may be irregular and infrequent; and (4) the degree of canopy opening that favors desirable regeneration, usually light demanders, and at the same time controls climbers and weeds (if indeed, such exist) has proved elusive.

The patchy occurrence of desirable natural regeneration in the moist forests of tropical Africa and America was recognized early (Champion 1934). A study in Nigeria found that most of the seedlings on hand were of middle-story species, not the outstanding dominants termed emergents (Jones 1950). Local variations in the abundance of regeneration not apparent in broad survey statistics were found in the moist evergreen forests of Venezuela (Rollet 1969).

Even where natural regeneration has been adequate, it has sometimes been disregarded as a source of a new crop. Teak *(Tectona grandis)* in India and Pakistan, for example, may adequately regenerate by seedlings, coppices, or root sprouts, yet stands have been regenerated by planting (Imam 1969).

Success with natural regeneration calls for more than the appearance of a new crop, as illustrated by early experience in what is now Sri Lanka (Holmes 1945). It was noted in 1921 that a carpet of seedlings appeared in openings in moist forests. Two years later it became apparent that cleaning these seedlings would be crucial to their survival. Treatment revealed that the regeneration occurred in patches concentrated near seed bearers. After 4 years, the remaining stand was even more spotty, a result of variations in light and animal damage. In the 5th year, a marked dry season caused further losses. By the 8th year, it was concluded that regenerating a stand was not a problem, but its survival through the first years was. Even in the 12th year, the saplings were still being choked out by weeds. Apparently, commercial timber production could not depend on untended natural regeneration.

Natural regeneration was attempted in the forests of Nigeria from 1906 to 1944, at which time a general failure was recognized (Oseni and Abayomi 1970). By 1957, Uganda was the only African country in which forests were managed on the basis of planned, natural regeneration (Anon. 1957e). By 1966, most African countries were promoting planting within existing forests (Galinato 1966). A proposal was made in what was formerly Zaire to convert land abandoned by shifting cultivators to naturally regenerated secondary forests by first establishing sparse plantations of eucalypts (Pierlot 1952).

In Uganda, authorities shifted to natural regeneration after 1952 because of costly plantation failures, including underplantings (Baur 1964a). Since then, the forests have been sampled to assess treatment needs, then refined before exploitation. Natural regeneration was found more plentiful than expected. Where regeneration was adequate, the overstory was removed in a single operation.

Similarly, in Queensland, Australia, generally adequate natural regeneration has occurred. Up to 2,200 trees per hectare 10 cm in d.b.h. or more remained after logging, of which nearly 200 were of cabinetwood species (Baur 1964a). Girdling of the undesirables and cutting climbers doubled the diameter growth of the selected trees.

In tropical America, attempts to induce natural regeneration have been extremely local and insignificant compared with plantation projects. A study of the causes of natural regeneration losses in *Swietenia macrophylla* in what is now Belize is of some interest (Wolffsohn 1961). Strips 6 by 36 m were cleared to the leeward of 10 seedbearing trees and subdivided into 6- by 6-m plots. Half the plots were treated with the persistent insecticide aldrin. The seedling crop that year ranged from 1 to 6 per plot in the untreated plots and 40 to 255 when the plots were treated. Seedlings were also abundant on abandoned logging roads, suggesting that many also escaped insects there.

Natural regeneration under extremely wet conditions (750 cm of rainfall annually) at low elevations in western Colombia was found adequate in quantity 2 years after logging (Ladrach and Mazuera 1985). Before cutting in the mature forest, there were about 1,400 trees per hectare 4 cm in d.b.h. or larger; 2 years after cutting, there were 6,800 trees. Only about 1 percent of these were sprouts. It was apparent that in order for new seedlings to enter the cutover stand before the vegetation again closes, germination would have to take place immediately after cutting, or certainly within 2 years. On this site, the volume in trees 13 cm in d.b.h. and more 15 years after cutting was half that of the mature forest, suggesting that by the 30th year, it would be equal to that of the mature forest (Anon. 1979e).

Experience in Peru offers further evidence that in moist forests, natural regeneration need not be a serious problem (Hartshorn and others 1986). Clearcutting strips 20 to 50 m wide, separated by 200 m or more, with full utilization of the wood yielded, led to regeneration at 15 months of 1,500 saplings of 50 cm or more in height, with 132 species represented. Although a local market for fuelwood apparently exists at the site, it remains to be seen how valuable for other purposes these species will prove.

The general inadequacy of high-quality, natural regeneration has led to three options: substitution, inducement, and planting, in that order (Dawkins 1958c). Substitution is appropriate where other potentially commercial species that reproduce well naturally are available. Elsewhere, research into induced regeneration of native desirables should be undertaken before natural regeneration is entirely abandoned. Studies should center on seeding, the ground environment, and canopy manipulation.

Even where natural regeneration appears to have failed, a shift to planting should be made cautiously. Plantations can produce higher yields, but their greater costs require land that is of better quality and more accessible than the kind of land that can produce naturally regenerated forests. The relative costs of the two practices, however, vary widely from place to place. Total costs are seldom included in such comparisons. In some areas, natural regeneration may prove less costly than expected (Kio 1976). Moreover, more of the cost for natural regeneration goes toward employment of unskilled workers. However, progress in genetic improvement of selected plantation species should, in time, make natural regeneration a less competitive option.

The process of natural regeneration is not fully understood. Local studies of phenology, seed dispersal, and relations to light, moisture, and forest gaps are needed. Guidance can be found in a collection of studies published in Mexico (Gomez Pompa and del Amo 1985).

In summary, the inducement of new regeneration of export-quality species by silvicultural techniques in moist forests has been successful only locally. However, in forests where seedlings and saplings are naturally plentiful, such as in Queensland, the Philippines, and parts of Malaysia, Sri Lanka, and Africa, their protection, stimulation by prefelling treatments, and liberation have been successful (Baur 1964a, Dawkins 1961d). The key questions are how much tending is required and how the benefit/cost relations compare with those of plantations and alternative agricultural land uses.

Refinement Treatments. Refining is the elimination of undesirable trees, climbers, and shrubs to foster complete site utilization by the desirable crop (Dawkins 1955b, 1958a, 1958g; Ford-Robertson 1971). It requires the allocation of growing space to promising immature trees at the expense of others (fig. 4–10). It is a varied practice that may include the elimination of giant relics left after logging, felling or killing unsound trees and those of inferior species, cutting back damaged stems, liberating desirables, thinning juveniles, and freeing seedlings. The practice is also commonly termed "improvement felling." In the Tropics, the term "selection felling" has in English been applied about as broadly as improvement felling for refinement.

A major argument for refining secondary forests rather than replacing them with plantations is the presence of an immature crop that replacement would sacrifice. Such stands may have a wide range of tree diameters, of which the largest may appear to be the most worthy of being brought to maturity. This situation, plus the common assumption that tree diameter and age are strongly related, has led to attempts to apply the selection silvicultural system in tropical forests, preserving an array of

Figure 4–10.—*Thinned white mangrove* Laguncularia racemosa *after removal of about half the basal area in poles and fuelwood.*

tree sizes and proposing periodic (polycyclic) partial fellings that both harvest the mature trees and liberate the immature ones. Nicholson (1979) concluded that the fact that a high proportion of cutover forest areas is composed of immature trees not released by logging indicates that silvicultural treatment is needed.

The place of refinement in silviculture is illustrated in figure 4–11 (Wadsworth 1966). Clearly, after a harvest that leaves an immature crop or where such a crop has volunteered, the remaining stand component of primary interest is the canopy trees. If the immature trees in the canopy are not adequate for the next crop, attention shifts to the understory. If this is adequate in species quality and density, it will generally need to be liberated by removing part or all of the overstory, removing unwanted trees or climbers, or thinning the crop trees themselves. In typical forests, more than one of these treatments are needed. For example, in Ghana, selection felling reconditioned the stands following logging, including releasing the crowns. However, this does not by itself lead toward (much less ensure) the development of a selection or all-aged forest (Osafo 1970).

Refining of irregular forests has been successful under favorable conditions in the dipterocarp forests of the Far East where logging was carefully controlled and cutting cycles were long (Liew 1973b). Almost everywhere else, however, the preservation of irregularity has been in disrepute, as described earlier in this chapter.

Refinement became widespread in the vast and increasing areas of cutover forests on lands not needed for agriculture or forest planting. The practice has been favored as a silvicultural option because it is less expensive than other practices, such as planting, making it under some circumstances the most profitable management course (Earl 1975). In modifying the forest gradually and conserving natural components, even when the goal is uniformity, refinement is a conservative departure from nature. It had an early origin throughout the Tropics, as indicated in appendix E.

Refinement has varied widely over time, beginning in 1880 and covering hundreds of thousands of hectares. From 1910 to 1947 in what is now Malaysia, refining included climber cutting, thinning, and cutting back second growth (Baur 1964a). By 1927, it was evident that a lack of followup had resulted in much wasted effort. Immature trees of good species were not adequate everywhere. Girdling was not always effective.

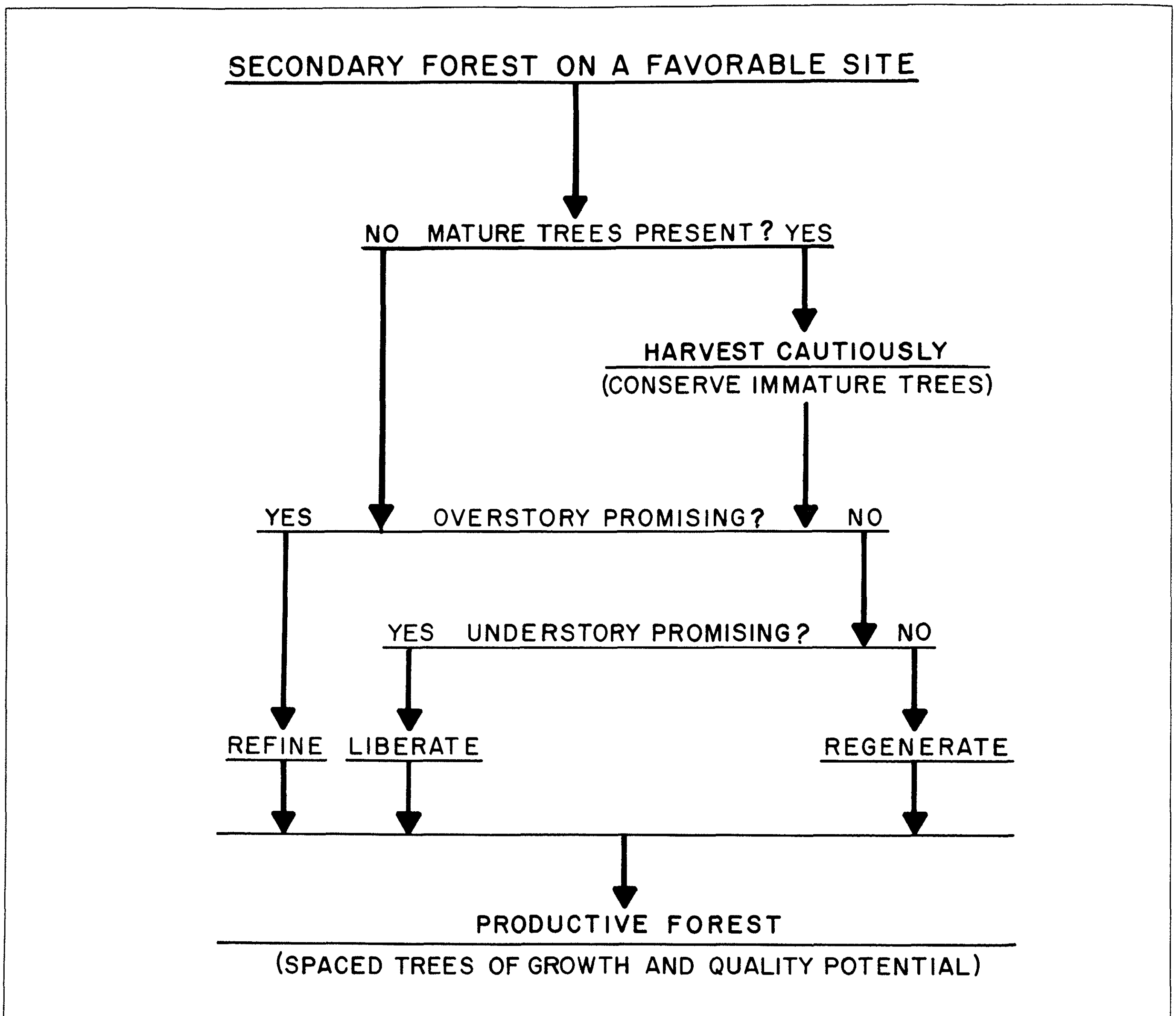

Figure 4–11.—*The place of refinement in secondary forest silviculture (Wadsworth 1966).*

Improved markets were making the girdling of poles unwise. The shift was to "regeneration improvement fellings," directed toward regeneration as well as improving the existing stand, a reversion to shelterwood. In 1930, the practice was to fell poles where there was a market, followed 2 years later with a light seed felling, a cleaning 3 or 4 years after that, a second seed felling in the 7th year, a cleaning in the 9th, and a final felling in the 10th, followed by more cleanings (Paul 1953).

By 1939, some 80,000 ha had undergone regeneration and improvement fellings in what is now Malaysia, and postwar studies showed that the proportion of rapidly growing species of *Shorea* had increased. The prospective productivity of about 5 m^3/ha/yr on a rotation of 70 years, although not as high as in plantations, was expected to produce forests much more valuable than their predecessors (Baur 1964a). After the Second World War, when it was seen that seedlings and saplings of some dipterocarps could cope with weed growth, there was a dramatic shift to clearcutting.

In what was formerly Zaire, irregular structure was retained. About 80 to 90 percent of the forests were allowed to develop naturally, and widely spaced strips were planted to selected species (Paul 1953). In francophone Africa, variable abundance of desirables after logging generally led to abandonment of natural regeneration and a shift to underplanting. In Nigeria, it was recognized in 1927 that regeneration was generally spotty, so gap plantings supplemented improvement fellings. Heavy fellings produced an impenetrable tangle and led to longer and longer periods of weeding and climber cutting until, by 1952, they had continued for up to 21 years. Experience in Ghana was similar. In both countries, it became apparent that success of refinement treatments depended on adequate regeneration at the outset.

Refining was applied in Suriname (Jonkers and Hendrison 1986). Initially it included cutting lianas and poisoning undesirable trees down to 5 to 10 cm in d.b.h. Seedlings and saplings of commercial timber species proved to grow too slowly to compete. Larger trees grew at rates of 1 cm or more in stem diameter, but tending costs were considered too high, so the shift was to plantations.

Soon planting was also abandoned because of the rising costs of clearing, planting, and tending (Jonkers and Hendrison 1986). What followed has been a testing of reduced-intensity, polycyclic management of natural cutover forests. Refinement is scheduled at 1, 8, and 16 years after logging. Only trees larger than 20 cm in d.b.h. are poisoned. Scheduled reductions in basal area for the first treatment were from 28 to 12 m^2/ha; for the second treatment, 7 years later, from 20 to 10 m^2/ha; and for the third, 15 years after logging, from 18 to 15 m^2/ha.

Reducing the basal area to 15 m^2/ha may require the poisoning of 100 trees per hectare (Jonkers and Schmidt 1984). Increased diameter growth on the trees that are left will continue for 8 to 10 years, then followup treatments will be needed. The mean annual diameter growth ranges from 9 to 10 mm. Three treatments several years apart each cost about 7 worker-days per hectare. The harvest, after 20 years, is expected to come from 13.5 trees per hectare, compared to only 2.7 harvestable trees after 25 years with no treatment.

Coupled with the revised refining technique under study is intensified logging, termed the "celos system" (named for the source institution, Centrum voor Landbouwkundig Onderzoek in Suriname), with a focus on reducing damage to the immature trees (Jonkers and Hendrison 1986). Preliminary inventories, mapping, trail layout, and direct supervision of felling direction and skidding practice significantly reduced logging damage. Where 3.4 commercial trees were removed per hectare, 82 percent of the remaining trees were undamaged. Where 16.2 trees were removed, 65 percent remained undamaged.

A recent study of the growth response of high forests to refinement (Synnott 1979) has shown that, within certain limits, reductions in stocking and basal area by felling and/or poisoning may sufficiently accelerate growth of the remaining trees, more than compensating for reduced basal area. Net basal-area growth per unit area under these circumstances increased with basal-area reductions.

It bears repeating that improvement fellings were recognized early only as a provisional treatment, mainly to utilize the available stock (Troup 1921). Refinement is not a silvicultural system in itself in that it does not ensure successive crops. Although repeated refinement of secondary forests should gradually increase the number of useful tree species and their seeds, there is no assurance that a new crop will develop and survive harvesting of the overstory.

Refinement invariably leaves the forest more open by eliminating unwanted trees to stimulate growth of the trees that remain. The elimination of relics may produce large canopy openings. Such openings may also stimulate (or possibly smother) existing seedlings of trees that might comprise the next crop. They may also make the forest floor warmer and drier.

Where refinement is directed toward monocyclic management, the ultimate harvest is intended to be total, producing exposure and logging effects similar to those in plantations. However, if advanced regeneration develops and logging is carefully controlled, an adequate new crop of young trees may survive and protect the site after the harvest.

Favored tropical species must be not only highly productive and potentially marketable but also fully site compatible rather than merely site tolerant. The ecological and technical knowledge about species and sites necessary to make refinements fully effective is not yet available. Until it is, all species that look good should be preserved so that they may be treated more judiciously in the future as more information about them comes to light.

Refinement to maximize production of useful wood ultimately reduces the representation of more than half the tree species and, therefore, probably also reduces forest diversity. Such simplification could eventually endanger the ecosystem. A reasonable compromise might be to leave (until the effects are better understood) the trees of understory species and some unmarketable overstory species, such as species of Palmaceae and opportunists, removing only those that clearly overtop the crop trees, possibly at little or no sacrifice to yields of useful wood.

The yields from refinement may be lower than those of more intensive technologies, but the required investments are also low and often more in tune with available financial resources (Palmer 1975).

A supplement to refinement in coniferous tropical forests is prescribed burning to reduce the understory or the accumulation of slash that might fuel an uncontrollable fire during dry, windy weather. Burning has a place when cautiously done under favorable weather conditions. However, on steep slopes prescribed burning can increase surface runoff and sediment loss. Even a low-intensity burn in a natural *Pinus oocarpa* stand in Honduras on slopes ranging from 10 to 40° raised the surface runoff from 1.7 to 5.0 percent and sediment loss from 80 to 1,732 kg/ha/yr (Hudson and others 1983).

Yield data from refined forests are not yet adequate to predict ultimate limits of timber productivity. However, higher yields will be required in the future. One way to raise average returns is to concentrate on only the best available sites. Another approach to higher returns is to increase the marketability of little used, rapidly growing species. This could also immediately increase the eligibility of stands for refinement.

Crop Adequacy. Experience in refinement, like that of silviculture in secondary tropical forests, has taught more what not do than what to do. As with silviculture, however, it is not clear that plantations are a better alternative everywhere. With improved markets raising values on more forest products and tree species, much of what was done in the past would now be done differently. Increasing public understanding of the non-commodity values of tropical forests brings about a recognition that preservation and management of tropical forest ecosystems are imperative to human welfare. Because it is improbable that a need for forest production will decline, subsequent sections of this text extract from past experiences those policies and practices for forest refining that deserve further study and testing in the search for optimum sustainable management of the forests for all their values.

The number of timber crop trees in a fully stocked, immature stand depends on their final spacing requirements and their expected mortality during the rotation. The number of trees of export size constituting full stocking at maturity is small. For 1,469 trees of 15, large, wet-forest, tree species in Puerto Rico, the mean crown-diameter-to-d.b.h. ratio is near 20 for trees 20 to 40 cm in d.b.h. with extremes of 5 and 39 (Wadsworth 1987; fig. 4–12). At a basal area of 25 m^2/ha and a crown-diameter-to-d.b.h. ratio of 20, no more than 90 well-illuminated trees of 60 cm in d.b.h. can be accommodated in a hectare. In tended forests, crop-tree mortality is remarkably low (Dawkins 1961c, Wilkinson 1960), and therefore, the number of saplings and poles need not be more than two or three times that of the final crop to ensure full stocking. Dawkins (1958c) has arrived at the number of trees that he feels are needed for full stocking to 80 cm in d.b.h. in Uganda (table 4–10).

In mixed stands, tending can concentrate on removing trees of little potential value because of species or form (Dawkins 1961c). This method, plus evidence that tended crop trees survive well, suggests that as few as 100 saplings and poles per hectare can result in full stocking at 60 cm in d.b.h. Danso (1966) considered 22 to 25 stems per hectare of commercial tree species 10 to 70 cm in d.b.h. worthy of silvicultural treatment in Ghana. However, he noted that because these trees may occur in dense groups, they may have to be thinned before reaching maturity.

In the Philippines, where there has been generally an excess of trees of 20 to 70 cm in d.b.h. before the first harvest, a goal has been to save 60 percent of them (Tagudar 1967). In Indonesia, the number of trees left for the next crop has ranged from 25 per hectare for those 35 cm in d.b.h and larger to 40 per hectare for those 20 cm in d.b.h. and larger (Soerianegara 1970). In Suriname, 200 to 500 "juveniles" (probably 10 to 20 cm

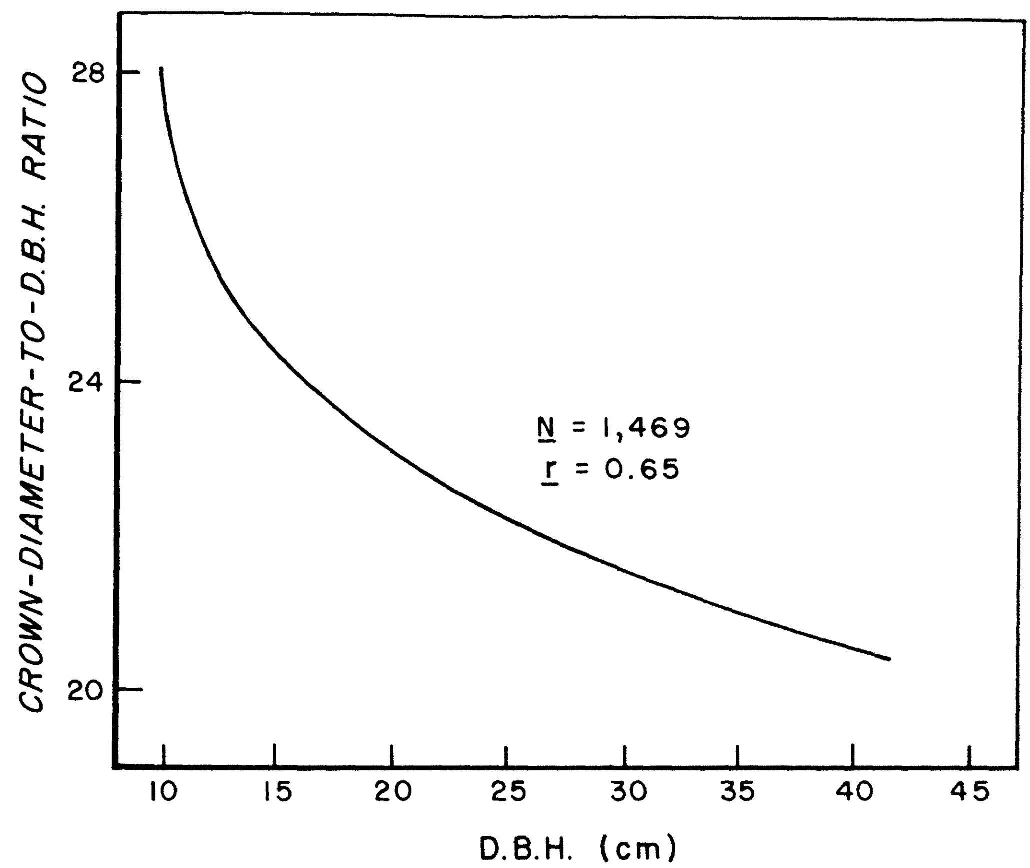

Figure 4–12.—*The uniformity of crown diameter-to-d.b.h. ratio for trees above 20 cm in d.b.h. (Wadsworth 1987).*

in d.b.h.) per hectare have been accepted as adequate. These have been tended in strips running east and west, 2 m wide and 10 to 20 m apart (Boerboom 1966). Should smaller trees at maturity be the objective, a larger number would make up the final crop (125 trees of 50 cm in d.b.h. per hectare), but because of lower mortality, the same number of well-spaced starters may prove adequate.

Something less than full stocking in secondary forests might still be preferable to the cost of artificially regenerating a full crop. Therefore, fewer crop trees may be worth tending, as they may well make a higher return on the investment than starting anew with planted trees. Wyatt-Smith (1960d) reported that in Malaysia, 40 percent seedling stocking at the time of felling corresponded to 55 percent stocking of saplings 5 years later, amounts he considered minimum.

In secondary volunteer forests that arose on cleared areas, the overstory ordinarily appears to have little crop potential. It is commonly a mixture of poorly formed pioneer trees, many of which mature at a small size.

Table 4–10.—Number of trees corresponding to full stocking in Ugandan forests

D.b.h. (cm)	No. of trees per hectare
0–10	2,000–25,000
10–20	200–400
20–50	100–150
50–80	50–75
>80	35–50

Source: Dawkins 1958c.

Attention there should be focused on the understory, where saplings of tree species of more advanced successional stages may be appearing from seeds recently introduced by animals. Some of these may produce marketable wood. If liberated early, they may also be capable of rapid growth.

The proportion of the secondary forests of the humid Tropics that contains adequate stocking may be larger than generally supposed. A systematic survey of 97,000 ha of secondary forests and abandoned coffee plantations 10 years old and older in Puerto Rico showed that about 52,000 ha were adequately stocked with trees of 21 species that were potentially marketable locally (although not for export) (Wadsworth and Birdsey 1985). Of this area, 24,000 ha were stocked with 100 poles per hectare or more (averaging 176) 12.5 to 27.5 cm in d.b.h. and 28,000 ha with 250 saplings per hectare or more (averaging 725) 2.5 to 12.5 cm in d.b.h.

Identification of Timber Crops. Early improvement felling emphasized eliminating trees rather than stimulating them. This reflected more confidence in identifying trees of little value than in selecting those that might prove most valuable at some future date. Because the trees in natural stands are generally crowded, eliminating what seemed worthless was considered an infallible step toward higher productivity of what was left. No doubt such treatment enhanced future timber productivity. However, this strategy generally ignored the possibility that the gaps thus produced would leave vacant microenvironments unsuited to the timber species or the habitat needed for animal life that contributed to the forest's well-being. Also, it was seldom known whether this kind of enhancement was cost-effective.

More recently, treatment has focused only on stimulating those trees expected to form the next crop. Concentrating on stimulating timber crop trees presupposes that they can be identified with certainty. For identification, a set of minimum qualifications for crop trees is needed. Such trees must be potentially superior to their neighbors and free from interference from other crop trees. The basic criterion for selection is that species of trees should be likely to be uniform in size at maturity, form, tolerance of competition, growth rate, freedom from insect and disease problems, and wood properties. The following considerations should guide species selection:

1. Include species with diverse characteristics and even doubtful future utility to preserve ecosystem stability and anticipate value changes

2. Include tree species whose products supplement rather than compete with plantation species

3. Include tree species that in nature grow to a larger diameter than the desired size for harvest, so maturity will be reached during youthful vigor

4. Include species with straight stems, an advantage even for fuelwood.

Freezaillah (1984) points out that 93 percent of the tropical forest volume is of little-known species. Most of this volume is wasted, suggesting potential gains from market development. Perishable woods can be treated with preservatives. Small trees and woods considered mediocre are becoming marketable.

Export markets for new species will develop only gradually as long as select timber supplies remain. For local markets, processing capacity must exist, preferably for products more valuable than chips.

The prospect that many tree species not now used *could be* used by the time present crops mature is supported not only by what has happened in the past but also by studies of existing stands. The closed forests of South America are contributing to the local economy far below their potential (Ramos de Freitas and others 1987). Research on wood properties and processing promises to increase productivity 10 to 30 percent without large investments.

Among the hundreds of tree species available, some will no doubt continue to be much more useful than others regardless of how great the demand for wood may become. This suggests that simplifying the natural composition of tropical secondary forests should increase their productivity. Such simplification, if cognizant of any adverse ecological consequences, should make subsequent silvicultural treatments more practical and comprehensible. An approach undertaken by the author to classify timber tree species of Paraguay by their apparent potential utility illustrates the process. The total number of timber species listed for the moist forests of eastern Paraguay was 230. These were then classified on the basis of existing (incomplete) information as follows:

- Tree species that in nature do not grow larger than 50 cm in d.b.h. or generally do not have a straight bole of at least 6 m—152 (class VII) (leaving 78)

- Of those left, species that produce woods having no apparent promise for any usable product—8 (class VI) (leaving 70)

- Of those left, species with woods clearly unsuited for industrial uses, such as furniture, plywood, or construction—10 (class V) (leaving 60)

- Of those left, species with woods of unknown suitability for such industrial uses—17 (class IV) (leaving 43)

- Of those left, species with woods adequate for construction but not for furniture or veneer—9 (Class III) (leaving 34)

- Of those left, species with woods considered acceptable for furniture or veneer but heavy or difficult to work, specific gravity 0.71 to 0.90—12 (Class II) (leaving 22)

- Of those left, species with woods considered superior for furniture and veneer, specific gravity 0.40 to 0.70—22 (Class I).

Under such a classification system, nearly 10 percent of the woods of the forest are in Class I. In all, 19 percent are in the three classes known to be of industrial utility. An additional 7 percent are of potential industrial utility, and 4 percent are of nonindustrial utility. The rest seem unlikely to produce more than fiber or fuel, both low-value forest products in moist regions. The total number of prospectively useful tree species then comes to 70, or 30 percent of the total. Others may be of some value only for roundwood, pulpwood, or fuel, but the first 70 may be equally suitable for these purposes. Such a classification system guides tentative assessments of the quality of secondary forests. To such a classification system should be added values for other products, such as palm hearts, fruits, or species critical as wildlife habitat.

Rejecting species with heavy wood is more justifiable than rejecting light-wooded species because expanding fiber uses and shorter rotations may favor light-wooded species of rapid growth. Balsa *(Ochroma lagopus)* is one of the world's lightest woods and yet is in demand for this very reason. In fact, much of the balsa found in secondary forests is less marketable because of its higher wood density. Light, pithy woods, however, will probably always be difficult to market. Dense woods may be in more demand in the future because of their potential energy content, but only if they grow fast enough to give high-energy yields per unit of time.

Many of the species considered potentially useful may be little used because their rarity in forests precludes the marketing of significant volumes. Such species should not be ignored in management, because rare species of value presumably can be made abundant.

Characteristics appropriate for further ranking of species within the groups mentioned include ubiquity, abundance on available sites, mature size, form, growth potential under full stocking, windfirmness, facility of regeneration, freedom from pest and disease problems, and responsiveness to silvicultural treatments. Most species may already have one or more of these characteristics; none may get high marks in all of them. For many species, some of this information is sketchy. Although initial classification may be provisional, it should improve as silvical characteristics and uses become better understood. In the meantime, however, misclassification within the select list is likely to occur only among species of similar potentials. Moreover, questionable species are seldom eliminated completely by treatment, so there remains time for adjustment.

Even the most liberal of species classification schemes recognizes only a fraction of the tree species as suitable for industrial timber. In Paraguay, it was 19 percent; in Puerto Rico, 16 percent. Thus, by discriminating against the other species, repeated refinement might ultimately reduce the number of tree species in productive forests to one-fifth or one-sixth of the original. Further refinement, favoring only the most preferred crop-tree species, might lead to nearly pure forests before the end of a rotation.

Favorable as such simplification may seem, it may not prove sustainable. In extreme cases, it may ultimately approach a monoculture with the corresponding risk of instability. Therefore, as studies indicate microsite preferences or tolerances for each crop-tree species, refinement should preserve a mix of adapted species.

The productivity of secondary forests is affected by stand structure as well as composition. For polycyclic management, the goal may be crop-tree-size groups similar in size and equal in number to the cutting cycles in the rotation, with the number of trees in each group producing a positive de Liocourt trend. For monocyclic management, the goal is a single harvest period, so crop trees might best be selected in part for the synchrony of their prospective maturity with the predicted time of harvest.

Long, straight stems are critical to industrial wood yield and of value for all other products, even fuel. Many broadleaf species of tropical America stop merchantable height growth while the trees are still small, because forking, rather than diameter, is the determinant of merchantability. The tendency for merchantable height to remain constant after a d.b.h. of 20 cm has been reached is evident in data for 1,600 trees of 15 species from moist forests in Puerto Rico (table 4–11; Wadsworth 1987). A tree with an unusually long, usable bole may simply reflect heavy shade during its youth, but it may also be genetically superior, a characteristic worth favoring in crop trees and their progeny.

Critical to the productivity of crop trees are their prospective growth rates. However, the prediction of growth rates as a basis for selection is not yet reliable. Growth rings in the wood of most species are not distinctive enough to gauge the growth rate. Comparisons of predicted and actual growth rates based on repeated tree measurements are rare. Units to express tree growth must be selected to avoid bias. Palmer (1975) notes the lack of comparability in growth between small and large trees when measured by d.b.h. in the absolute or as a percentage. He sees basal-area growth as a better measure than diameter, one that is also closely related to volume and commonly linear with time. He concludes that basal-area growth as a percentage may be a better measure still, because stem basal area apparently is linearly related to both nutrient and energy resources (root and crown area). Basal-area growth as a percentage would appear to reflect net wood productivity per unit of forest area occupied and, thus, the relative efficiency with which each tree utilizes its space. In a 24-year study of 1,600 trees of 14 timber species from moist forests of Puerto Rico, mean basal-area growth as a percentage was fairly constant for trees between 10 and 40 cm in d.b.h.

Table 4–11.—Merchantable height by d.b.h. of 1,600 trees of 15 species from moist forests in Puerto Rico

D.b.h.	Merchantable height (m)	
(cm)	Mean	Extreme[a]
20	5.0	9.8
30	6.3	11.1
40	7.0	11.8

Source: Wadsworth 1987.
[a]Upper 95-percent productivity limit.

Free growth over long periods or for groups may vary little among species (Palmer 1975). Nevertheless, the wide variation that is commonly observed from tree to tree suggests a large, untapped growth potential that might be released by the silviculturist. However, the rapid growth of some trees may partly be made possible by the slow growth of others. To the degree that this proves true, the growth of crop trees may not benefit much by the removal of the less promising, slow growers.

A circumstance widely overlooked in assessing diameter growth is that means are underestimates because it is only trees growing faster than the mean that make up eventual crops. Conceivably the top quartile is more indicative.

The study of 1,600 trees in mixed moist forests of Puerto Rico showed the maximum basal-area growth (as a percentage) for trees 10 cm in d.b.h. to be far above the mean (fig. 4–13; Wadsworth 1987). The 24-year, basal-area growth of 43 trees of the same species, all in an intermediate canopy position and all between 10 and 20 cm in d.b.h., ranged from 0.7 to 6.9 percent per year, almost a tenfold spread. In this same forest, an attempt to relate 24-year, basal-area growth of individual trees, as a percentage, to the basal area of the trees around them, as determined by a three-diopter prism, explained only 0.1 percent of the variation, suggesting that tree growth rate and surrounding stand density are unrelated. Studies of 16 tree species in 22 forests in Uganda revealed some trees growing 25 times as rapidly in diameter as others (Dawkins 1964a). It was concluded that the fastest growing trees are the most efficient genotypes standing on the most favorable microsites.

In a study of 512 trees in mixed subtropical wet forests and rain forests in Puerto Rico, it was found that basal-area growth of individual trees was about the same for one 12-year period as it was for the subsequent 12-year period (both between hurricanes). This suggested that each tree, when released after an indeterminate, early period of suppression, fills an available canopy and soil

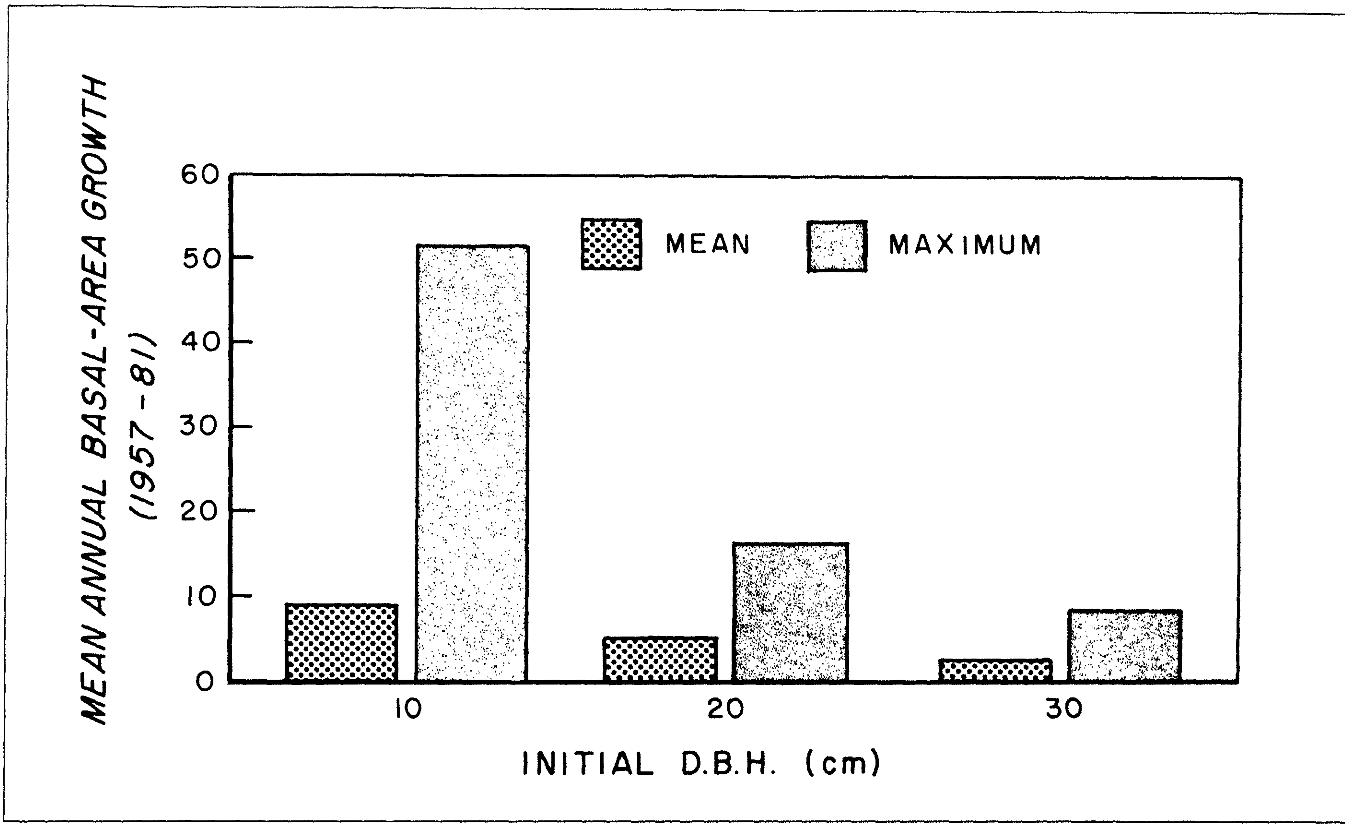

Figure 4–13.—*Comparative mean and maximum tree growth of 1,600 trees in a mixed moist forest of Puerto Rico (Wadsworth 1987).*

niche and then increases stem basal area at a relatively constant rate. From this assumption, a hypothetical growth period was derived for each of these trees by dividing its current stem basal area by its recorded mean annual basal-area growth for the previous 24 years and subtracting the resulting number of years to indicate when, had it always grown at about that rate, it might have started growing. When the numbers of trees were arrayed by these hypothetical, growth-starting dates, unusually large numbers of trees appear to have started at the time of past hurricanes: 1899, 1916, 1928, and 1932. This suggests that the hypothesis may have merit. If so, current tree growth in stable forests may reflect the size of a relatively constant niche, in terms of root and crown space, available to the tree since it was released.

A lack of correlation between tree growth and surrounding stand density has already been described. Wide variation in apparent productivity between individual trees found in Uganda and Puerto Rico is evidently virtually independent of stand density (Dawkins 1964a). In Nigeria, the basal areas of trees surrounding selected trees accounted for no more than 11 percent of the variation in growth, usually for much less (Lowe 1966). In thinned stands, "competition" so measured proved to be even less of a contributor to growth variation. Eliminating the variation due to species and basing the study on species of *Khaya* alone still failed to distinguish any significant influence of the basal area or numbers of relascope-counted surrounding trees on crop-tree growth (Kemp and Lowe 1973). One possible explanation of this apparent paradox is that competitive stress tends to equalize, stand density being greater on good microsites. This could offset any tendency for an inverse relation between surrounding stand density and crop-tree growth in closed ecosystems.

More profound investigations in Nigeria, using pattern analyses, showed that basal-area growth of surrounding trees was a better indicator of competition than either their summed diameters or basal areas (Lowe 1971). Low density appeared to benefit intermediate and codominant trees more than either the dominants or suppressed trees.

The position of tree crowns in the forest canopy has also been suggested as a predictor of growth rates. A strong relation between canopy position and mean d.b.h. growth was reported early by Wadsworth (1947b). In wet forests in Puerto Rico, the codominant trees grew 92 percent as fast as the dominants, the intermediates 65 percent, and the suppressed 35 percent.

An inverted 90° cone with the apex at the base of the crown was conceived in Uganda as a means for mathematically expressing the degree of crown exposure (Anon. 1956d). But again, a wide range of growth was found to be independent of this measurement (Dawkins 1964a). The only rapidly growing trees were those clearly dominant or with very large crowns (Dawkins 1958c). Beneath the top canopy, crown position appeared to be of little significance to growth rates.

Position in the canopy as a basis for predicting tree growth is confounded by tree size, because the dominants or exposed trees tend to be large and the suppressed ones small. A study with *Khaya* in Nigeria showed that canopy position significantly affected the regression between initial tree basal area and subsequent basal-area growth (Lowe and Walker 1977). Other studies in Nigeria gave no evidence that the vigor of dominant trees is inherent. Their growth superiority was much less among clones lacking genetic variation (Lowe 1971).

When tree growth is related to the space required (i.e., expressed in annual basal-area growth as a percentage of the mean basal area), the relative efficiency of codominant and intermediate trees is brought out. The study of 14 timber species in moist forests in Puerto Rico covering the period from 1958 to 1982 showed that trees that were initially dominant had a mean annual increase in basal area of 3.6 percent; codominants grew 3.6 percent, intermediates 2.9 percent, and those suppressed 2.1 percent.

Crown dimensions as an expression of leaf area per tree have also been studied as tree-growth predictors. The suitability of overall crown area for this purpose was studied in detail in Uganda (Anon. 1956d, Dawkins 1958c). Crowns were classified by grading their apparent capabilities for growth or need for release. Wide, circular, deep crowns were considered perfect. However, there has generally been little success in correlating individual tree growth with crown factors (Dawkins 1963a). In Nigeria, a strong correlation between crown and stem diameter appeared to confound the relation between crown diameter and growth (Kemp and Lowe 1973, Lowe 1966). No significant amount of individual tree growth variation could be ascribed solely to crown diameter or crown height (Lowe 1967a).

Initial tree diameter or basal area is the strongest single known predictor of tree growth; and in this, trees in natural forests do not appear to differ greatly from those in pure, even-aged stands (Lowe 1966). A study of natural forests and teak coppices showed that variation in basal-area growth of individual trees was about 70 percent resolved by their own initial basal areas; i.e., growth was apparently largely a function of initial size. A later study of *Khaya* in Nigeria showed that initial basal area accounted for 54 to 60 percent of the variation in basal-area growth over 6- and 14-year periods, respectively (Lowe and Walker 1977). Another study determined that the rapid growth attributed to large trees applied to all trees, not just to crop trees alone (Palmer 1975).

Other variables have been considered as indicators, causes, or results of differing growth rates of trees in secondary forests. Mervart (1969) points out that the response of individual trees may change with time or age. Ruehle (1972) suggests that the importance of healthy roots has been underestimated. He points to plant-parasitic nematodes as possible suppressants of fungal symbionts, such as mycorrhizae, which are known to be present on the roots of most tree species. In Nigeria, climber infestation was found related to growth rate (Lowe and Walker 1977). Studies of 234 dipterocarp trees showed that variation in specific gravity of wood was an indicator of past growth (Virtucio 1976). It was found that specific gravity reflected 51 percent of the variation in basal-area growth and 48 percent of volume growth. The lighter the wood, the faster the growth.

Frustration with seemingly logical predictors of individual tree growth has led some observers to morphological tree features. In the wet forests of Puerto Rico, it was observed that the fast-growing trees may have exceptionally straight boles free of blemishes and epiphytes (Wadsworth 1953). In west Nigeria, it was also found that factoring in stem form improved growth predictions over those based on initial basal area alone (Lowe and Walker 1977). Better stem form meant faster growth.

These diverse studies have so far failed to reveal any single, universally reliable criterion for predicting relative growth rates of tree "A" versus tree "B." To the contrary, they clearly show that individual trees may grow at very different rates regardless of perceived causes, such as visible site factors, species, tree size, and density of neighboring trees. Some interesting conclusions and hypotheses resulting from these many studies are as follows:

- Tree growth may be sufficiently random to frustrate any attempt to interpret it systematically (Mervart 1969, cited by Palmer 1975).
- The individual-tree approach to growth prediction may have little practical potential in tropical stands containing diverse species and age classes (Gerrard 1968).
- Stand projections based only on mean growth (average time of passage from one size class to the next) are erroneous for individual trees. Passing through broad diameter classes does not affect individual tree performance within the previous diameter class. Only the worst and best tend to remain in rank (Lowe 1977, Mervart 1972).
- Reducing the total error of growth estimates via regression analyses of the diameter-growth relations has limited possibilities (Mervart 1972).
- The "smoothing" effect of long periods of measurement on growth should not be overrated. The ever-changing trends in individual tree growth tend to maintain the variation of the aggregate growth almost the same as over shorter periods (Mervart 1972).
- Trees within a stand apparently establish early a growth rate "pecking order" that varies with shade tolerance, a situation that may be difficult or almost impossible to alter by silvicultural treatment.
- Silviculture may only be following a pattern already formed by the crop itself. Departures from this pattern may impair overall stand growth (Lowe 1966).
- Only very early release can have much influence on growth rate (Lowe 1966).
- Even drastic canopy manipulation may fail to significantly affect the growth of some trees (Dawkins 1963a).
- If the prospective influence of silvicultural treatments on the growth of secondary forest trees proves limited, then treatments should be based on the local profitability of management alternatives rather than on the benefits of silvicultural treatment (Lowe 1966).

Obviously, the search for criteria that precisely predict growth of individual trees has not been successful. As a result, the process of selecting and treating crop trees has not yet attained its potential as a means of increasing productivity in secondary tropical forests. Until this can be done, the productivity of secondary forests will suffer when compared with that of plantations. Nevertheless, even where plantations are a feasible alternative, secondary forests remain complementary, a source of different woods and other necessary benefits. Moreover, it appears that early and repeated liberation of crop trees, however imperfect may be their selection, has not been fully tested and might yet greatly increase yields.

Until greater success is attained in selecting crop trees on the basis of prospective growth, other more obvious criteria may still be beneficial in stands as yet untreated. In such secondary tropical forests, the first steps generally involve improving composition, structure, and spacing. Tree selections made this way should have no inherent bias against those of rapid-growth potential, so the process at least should not be dysgenic. Better prediction is still urgently needed and warrants further study. Absolute crown size or its relation to d.b.h. merits priority.

Regeneration Assessment. Because most efforts to regenerate natural tropical forests have been concentrated in the Eastern Hemisphere, assessment techniques for timber management have not been widely applied in tropical America. For this reason, this section describes in some detail practices used elsewhere that would appear applicable to this region. The emphasis of Eastern Hemisphere systems on seedlings and saplings as well as on poles and larger trees appears equally appropriate for tropical America. Also, the success of the more recent diagnostic techniques in the East suggest that they may be universally adaptable.

The adequacy of stocking and horizontal distribution of crop trees and the need for tending have been assessed by various sampling techniques. By 1944, assessment of natural reproduction in India had developed an "establishment stocking factor" (Prasad 1944a). The basic sample was a 2-m square within which seedlings, established saplings (those <3 m tall), and established trees (>3 m tall) of crop species were counted. The mean height of the established saplings divided by 3 m and multiplied by the percentage of the squares with established trees produced the establishment stocking factor.

Techniques termed "diagnostic sampling" appeared in what is now Malaysia about 1950 as improvements in enumeration practices that had begun as early as 1930 (Barnard 1950a). Regeneration sampling was in use in what is now Cameroon in 1952 to distinguish areas for natural regeneration or for planting (Morellet 1952).

In what is now Malaysia, systematic sampling was done as a preliminary to enrichment of cutover forests. Natural regeneration neglected during the Second World War was found capable of coming through (Wyatt-Smith 1958b). Three sampling levels were commonly used (Barnard 1954, Majid and Wyatt-Smith 1958). Linear sampling, millacre (LSM) plots (4 m^2 or 0.0004 ha) were taken before felling to inventory commercial tree species seedling regeneration to a height of 1.5 m. One crop tree was chosen per plot. Adequate stocking required a selected tree in at least 40 percent of the LSM plots, indicating about 1,000 selected trees per hectare.

After harvesting, linear sampling, quarter-chain plots (LS 1/4), about 5 m square, or 0.0025 ha, were established to ascertain the stocking, composition, development, and competitive status of commercial saplings and small poles from 1.5 m tall to 10 cm in d.b.h. Adequate stocking required that 60 percent or more of these plots have a selected tree, corresponding to 240 per hectare (Wyatt-Smith 1960a).

Five to 10 years after harvesting, a third set of plots was measured. These linear sampling, half-chain plots (LS 1/2), about 10 m square, or 0.01 ha, were designed to ascertain the status of commercial large poles and trees 30 cm in d.b.h. or more. Seventy-five percent or more stocking was considered acceptable, corresponding to 75 trees per hectare. The LS 1/2 samples have provided: (1) density and composition of the overall stand; (2) stocking, composition, size, and distribution of the crop trees; and (3) urgency and degree of treatment required for crop trees (Wyatt-Smith and Vincent 1963). The LS 1/2 plots sampled 10 percent of the forest and were located on lines spaced 200 m apart. They were set up permanently in the field to permit resampling at intervals of 10 to 20 years. Each chosen tree was scored as follows:

5 = Tree suppressed by larger, sound trees of equal quality outside sample area.

4 = Crown good and would improve with treatment, but this is not urgent and may not be necessary.

3 = Crown good but not full and would improve with immediate light increase, but delay up to 5 years is possible.

2 = Crown deficient, requires immediate moderate treatment.

1 = Crown poor, requires immediate, drastic treatment.

0 = Crown very poor, probably incapable of responding.

Diagnostic sampling was introduced from what is now Malaysia into Uganda and Queensland, Australia (Dawkins 1961c). In Uganda, it was intended primarily to: (1) evaluate stand condition, (2) assess whether regeneration is adequate to replace the crop to be harvested, (3) determine what treatment may be required, or (4) determine what tending is appropriate to establish and develop the stand (Hughes 1961). The system was designed to provide a set of permanent plots to facilitate remeasurement if necessary and to set up a bookkeeping system to ensure accurate records and speedy analyses.

The standard sampling plot was 10 by 10 m, or 0.01 ha; plots straddle lines paced 400 m apart (Dawkins 1958f, 1958e). Halves of the plot on both sides of the line were further divided into two 5- by 5-m plots (0.0025 ha). Subsampling was so planned that approximately a 0.001-ha sample is taken of seedlings to 1.5 m tall, a 0.00625-ha sample of saplings 1.5 m tall to 20 cm in d.b.h., a 0.0125-ha sample of poles 30 to 50 cm in d.b.h., and a 0.025-ha sample of trees larger than 50 cm in d.b.h. (Walker 1962). Within each 10- by 10-m plot, a "leading desirable" was selected, and the stems in the plot that equal or exceed the d.b.h. of the leading desirable were counted. For each leading desirable, the diameter class, crown position, and degree of independence were recorded.

It was also in what is now Malaysia that linear sampling was developed as a means of assessing immature trees, already described in some detail (Barnard 1950b). It was assumed that fully stocked stands contain 2,500 seedlings (less than 1.5 m tall) per hectare, 400 saplings (over 1.5 m tall and up to 10 cm in d.b.h.) per hectare, or 100 poles (10 to 50 cm in d.b.h.) per hectare. The size of square plots along adjacent transects for each of these three classes was set at the corresponding proportion of a hectare per tree, or 1/2,500, 1/400, and 1/100 ha. For intensive sampling, plots along transects were spaced 100 m apart, corresponding to a 2-, 5-, and 10-percent sampling, respectively, for the three plot sizes. For extensive sampling, the distance between seedling plots along the transects was set at 400 m, or a 0.5-percent sample. For saplings and poles, the distance was 200 m, or 2.5- and 5.0-percent sampling, respectively. Within the sapling plots, the desirable saplings were recorded by size, as 1.5 to 3.0 m tall, 3.0 m tall to 5 cm in d.b.h., or 5 to 10 cm in d.b.h. For the poles, the size classes recorded were 10 to 20 cm in d.b.h., 20 to 30 cm, 30 to 40 cm, and 40 to 50 cm. Because one select tree per plot was considered full stocking, the degree of stocking of the area corresponded to the number of stocked plots as a percentage of the total. A secondary tree was selected and recorded if present (Barnard 1950b).

Hutchinson (1991) defined diagnostic sampling as an operation intended to estimate the potential productivity of a stand. He used diagnostic sampling in the American Tropics for the following purposes:

- To establish priorities for beginning silvicultural operations in order to optimize productivity and plan where to apply each operation
- To outline a suitable initial sequence of silvicultural operations
- To estimate an overall cutting cycle in relation to the ingrowing classes of desirable trees.

Hutchinson prescribed five steps in diagnostic sampling as follows:

1. Establish representative 10- by 10-m quadrats, at least 100 and preferably more.
2. Register the best of any trees larger than the maximum cutting diameter; note species, health, and stem quality.
3. Classify the leading desirable in each quadrat as a tree, sapling, or seedling. Select a tree before a sapling. If none, record as unstocked and distinguish potentially productive from permanently unproductive quadrats.
4. Record the d.b.h. of the leading desirable.
5. Record the crown-illumination class (vertical and lateral, vertical, partial vertical, oblique, and no direct) of the leading desirable.

Summarizing these data yields information as to the trees ready for harvest, large trees that could possibly yield a commercial harvest in the future, stocking of large noncommercial and defective trees hindering development of seedlings, and the adequacy of the illumination of the leading desirables.

The assessment technique in the rain forests of northern Queensland used plots 5 by 5 m square laid out contiguously on lines (Nicholson 1972). All trees 20 cm in d.b.h. or more are recorded.

Linked to diagnostic sampling is dynamic sampling, measuring large-scale changes in the forests over time. Developed first in Queensland, it is a form of continuous forest inventory based on permanent plots sited systematically throughout all productive forests and measured by permanent inventory teams at regular intervals (Dawkins 1961c). Plot sizes have been generally 0.08 ha in Queensland, 0.4 ha in what is now Peninsular Malaysia, and 1 ha in Uganda and Sabah (Dawkins 1961c). With emphasis on the crop trees, such sampling can provide a wealth of management information at minimum expense.

Composition Improvement. Initial silvicultural efforts in mixed tropical forests commonly have been directed at increasing the representation of the few most desirable species at the expense of the many inferior ones (Wyatt-Smith 1958a). The potential of this practice is seen in moist forests of Suriname, where only a third of the growing stock larger than 35 cm in d.b.h. was composed of commercial species (Schulz 1967).

Early concern with the consequences of eliminating species was expressed at the Eighth All-India Silvicultural Conference of 1951, already cited (Rosayro 1952). The conference warned that any radical departure from selection fellings in evergreen forests should be made with full realization of the grave risk of disturbing the delicate ecological balance that exists and of causing irreversible changes in the floristic composition of the forests to the possible detriment of their long-term productivity. An earlier warning had been sounded in what is now Malaysia that species generally wiped out in tending should be left in mixture with *merantis* (Mead 1937). Leaving an understory of poles of noncommercial species was also suggested to reduce the risk of epidemics.

The selection system appeared to critics in India to be but a screen covering drastic forest modifications (Stracey 1959). When selection cuttings were followed by fellings and girdlings to favor the next crop, the tendency was to produce uniform-sized crops of a few species. Stracey opposed the radical elimination of all but a few valuable species. A longer transition period, he thought, would permit a multispecies crop with a more desirable, broken, and irregular profile. Wyatt-Smith (1958a) recognized these risks but countered that it was not possible at the outset to base silvicultural prescriptions on ecological studies that had so far yielded only tentative results.

Early refinement of rain forests in what is now Malaysia, including climber cutting and poisoning of overmature, defective, inferior, and weed trees, significantly affected the composition of the dominant and subdominant stand (Wyatt-Smith 1958c). In the 5 years following treatment, the desirables in one forest increased from 58 to 64 percent, whereas in an untreated forest, they declined from 57 to 38 percent.

Trees of little or no foreseeable commercial value may be so dominant in secondary tropical forests that eliminating them in one treatment may create undesirably large breaks in the canopy, and subsequent regrowth of similar species or vines could smother remaining crop trees. Killing trees by girdling or poisoning is preferable to felling, because openings appear gradually and are smaller. Where heavy harvest cuttings are made, openings may be so large and advanced growth so damaged that special measures, such as underplanting, may be needed to ensure that a new crop quickly dominates.

Experience in the secondary forests of Puerto Rico further confirms the degree to which representation of the desirable species may result from first refinement treatments. In a thicket of saplings and small poles where a good fuelwood market was at hand, treatment increased the representation of desired timber species by 33 percent, and 6 years later, the volume growth of the treated stand exceeded the untreated stand by 9 percent (Marrero and Wadsworth 1951). The first improvement felling in more advanced stands in a moist secondary forest in Puerto Rico removed 75 percent of the trees of undesirable species and an even higher percentage of basal area (table 4–12; Anon. 1958i). The desirables were thinned by about 28 percent. Although the residual basal area is low, there are enough desirable trees to take over the entire stand (assuming they are well spaced) if further treatments are applied. The average d.b.h. of the desirables declined from 16.3 cm to 15.7 cm, indicating that some of the desirable trees removed were of above average size but of poor form. The increase in the volume-to-basal-area ratio (m^3/m^2) shows increased average usable stemwood height in the remaining desirables.

Liberation. To liberate means to release or set free. Silviculturally, "liberation" is defined as a cutting that relieves young growth from overhead competition (Ford-Robertson 1971). If regularly practiced, liberation can maximize growth rates in natural forests (Baur 1964a).

Liberation is a major objective in a broad range of refinement treatments. It is the primary reason for eliminating relics and may be the main motive for tending immature crops. Liberation is founded on the common belief that tree diameter growth is directly related to crown position and probably inversely related to crowding or stand basal area (Dawkins 1957). Pronounced anomalies do exist, however, e.g., stagnant emergents standing adjacent to growing subordinate trees of the same species with apparently the same crown quality (Dawkins 1961c).

Liberation is seldom the sole objective of silvicultural treatment however. In tending secondary tropical forests,

Table 4–12.—Stand composition improvement from forest refining in a moist secondary forest in Puerto Rico

Index	Before treatment	After treatment
No. of trees per hectare ≥10 cm in d.b.h.		
Desirables	430.0	311.0
Other	368.0	91.0
Percentage desirable	54.0	77.0
Basal area (m^2/ha)		
Desirables	9.0	6.0
Other	6.0	1.0
Percentage desirable	60.0	86.0
Mean d.b.h. of desirables (cm)	16.3	15.7
Ratio of volume to basal area of desirables (m^3/m^2)	2.6	3.0

Source: Anon. 1958i.

it is not enough to concentrate only on freeing individual trees from competition (Dawkins 1958c). The crop as a whole must be kept in mind. This concept may mean retaining more trees, some apparently less productive than others, as insurance or to favor some balance of tree sizes or species diversity.

Liberation of young trees has been tested most widely in the Eastern Hemisphere. In India, "tending" (which includes liberation) was applied in the 1940s wherever natural regeneration was present and was continued through the sapling to the pole stage (Griffith 1947). In what is now Malaysia, selection fellings in 1937 were done in advance of a partial commercial removal of the overwood to assist regeneration (Wyatt-Smith 1961a). In dipterocarp cutovers in Sabah (Nicholson 1965b), the best treatment sequence has been climber cutting and tree marking 1 to 2 years before felling, poison-girdling 3 to 6 years after felling, and liberation and other refinement of the rising crop 10 to 15 years after felling (Fox 1972, Hepburn 1973). The impact of release is seen in a stand logged in 1958 with relics poisoned thereafter (Fox 1972). The basal area averaged 19 m^2/ha in 1966, before 395 crop trees per hectare were released. Elimination of all trees competing with these called for the removal of 8 m^2/ha of basal area, or about 45 percent of the stand, leaving 9 m^2/ha of basal area in crop trees.

The rain forests of Queensland generally have enough regeneration to make liberation preferable to replacement (Henry 1960). Cutover stands may retain a basal area of about 50 m^2/ha with about one-third of the species marketable. Useless stems are then removed, and additional liberation may be done. In Uganda, liberation of existing advance regeneration has been adopted on a large scale (Earl 1968) because of difficulties with line and group planting. Well-formed desirables are marked with paint and charcoal burners remove any unmarked trees, thus precluding later damage.

Liberation treatment in tropical America began early in Guyana, Puerto Rico, Suriname, and Trinidad. In Trinidad, improvement of degraded forests on sandy soils by refinement began in 1932 (Beard 1944b). Natural regeneration at first had to be freed from grass and vine competition. Later, excess shoots were removed, competition between saplings was reduced, and palms were eradicated. After four treatments over a 10-year period, the number of saplings of economically valuable species 5 m or more in height averaged more than 70 per hectare. More recently, clearcutting of Trinidad's mora forests has been abandoned in favor of irregular stocking. Crop trees for future harvests were left and liberated, beginning 10 to 15 years after the initial harvest (Bell 1972).

Crown-diameter-to-d.b.h. ratios for the desirables have been used in Trinidad to determine spacing and maximum basal area consistent with crown exposure (Bell 1971). Under a system of triangular spacing that allows circular crowns to touch (utilizing 91 percent of the total land area), a crown ratio of 17 for *Sterculia* corresponds to a maximum desirable basal area of 32 m^3/ha. For *Dacryodes,* with a crown to d.b.h. ratio of 19, the maximum desirable basal area would be 25 m^2/ha. For the Lauraceae, with a crown-to-d.b.h. ratio of 20, it would be 23 m^2/ha.

On the South American continent, information regarding liberation cuttings is available chiefly from Suriname. A 1958 study (Anon. 1959j, 1961e) showed that only slight release induced the germination and vigorous growth of opportunists such as species of *Goupia, Qualea, Schefflera,* and *Simarouba*. The seedlings and saplings of preferred species required a second liberation. The cost of complete tending was considered excessive, so the treatment was applied only in east-west strips 1 to 3 m wide separated by distances inversely related to the abundance of desirable regeneration, generally 10 to 20 m. Within the strips, all weeds were cut and all undesirables from 10 to 20 cm in d.b.h. were removed, but no large openings were made (Boerboom 1964). Crop trees were sometimes pruned. The strips were tended twice in the first 2 to 3 years following the first liberation cutting. Three or 4 years later, after most of the poisoned trees were gone, the small, unwanted desirables were eliminated. There is no evidence that this practice pays, but it stimulates regeneration of light demanders that should mature in 30 to 40 years.

Before 1960, liberation tests were begun along the Amazon (Pitt 1961b). Results were promising with *Virola,* a species with regeneration already present in patches, and *Goupia,* a species that is not preferred in Suriname but that is a promising light demander in gaps in lower Amazon forests.

In Puerto Rico, liberation practice evolved from highly subjective judgment as to what was adequate (Wadsworth 1947a, 1958). From the 1930s to the 1950s, emphasis was on reducing stand density by eliminating apparently unproductive trees, including mature and overmature trees and trees of poor form and inferior species. Not all unproductive trees could be eliminated in a single treatment without serious weed invasion. By 1958, the guidelines were as follows:

- Treat only forests where tree crowns touch.
- Limit canopy openings to 8 m in diameter, except where required by the removal of a single large tree. Eliminate no trees adjacent to such openings.
- Harvest or eliminate trees larger than 50 cm in d.b.h. but only selectively within dense groups of merchantable species.
- Maximize representation of the desired sawtimber species in the next crop.
- Retain a mixture of desirable species in the crop.
- Strive for balanced structure with approximately equal basal areas of crop trees in each d.b.h. class between 10 and 50 cm.
- Eliminate trees that overtop crop trees.
- Give canopy desirables crown freedom averaging 2 m.
- Eliminate useless species and those usable only for fuel.

Only those forests containing at least 100 trees per hectare 10 cm in d.b.h. or larger of desirable species have been silviculturally treated in Puerto Rico. Test compartments have been demarked temporarily in 0.04-ha squares on lines 20 m apart. Within each square, up to 10 crop trees were selected. Each must be of a species on a selected list of 25, be between 10 and 50 cm in d.b.h., have at least 5 m of straight bole, and be at least 2 m from other crop trees. Among the selected trees, priority was given to their position on the species list; however, to preserve diversity, no more than 4 of any species were selected unless the total were less than 10. Next, the trees were ranked according to merchantable height, d.b.h., and regularity of spacing, in that order. Then, each crop tree was liberated by eliminating all "competitors," defined as noncrop trees as tall as or taller than the crop trees and closer than the spacing indicated in table 4–13.

Table 4–13 was derived empirically from local observations and other information on maximum basal area, allowing for rapid individual tree growth. Maximum tolerable basal area is less for small trees than for those nearing maturity. At the time this table was developed, the influence of the crown-diameter-to-d.b.h. ratio on growth was not recognized, but the spacings selected (triangular) were later found to correspond closely to those ratios for local timber trees. This density corresponds to the maximum desirable basal area for the principal species, *Dacryodes excelsa,* based on its crown-to-d.b.h ratio of 19. The ratios for a group of species are 26 for trees of 10 cm in d.b.h. and 20 for those at maturity (60 cm in d.b.h.). The minimum separations shown are rounded to facilitate use in the field.

Table 4–13.—Spacing guide for liberation of crop trees in Puerto Rico

Summed diameters (cm) ($D + d$[a])	Minimum separation (m)
20–39	3
40–59	5
60–79	7
80–99	8
>100	9

Source: Wadsworth 1958.

[a] D = d.b.h. of a crop tree and d = d.b.h. of each of its noncrop neighbors.

A forest liberated by this technique may not "look" as good as one where all apparently unproductive trees have been eliminated, because trees not interfering with the crop trees remain. However, because these trees, all shorter than the crop trees, are not believed to be detrimental to crop productivity, their immediate elimination is unnecessary. Left alone, they constitute diversity and may help stabilize the ecosystem or possibly even increase in marketability.

The intent in Puerto Rico has been to repeat liberation at 10-year intervals. As the remaining trees grow, more of the noncrop trees impinge on the increasing space required by the crop trees and become due for elimination. Sooner or later, a choice must also be made as to which of the excess crop trees are to be eliminated (and harvested if marketable). Those apparently least in synchrony with the prospective eventual harvest date for the crop are least worth keeping in the stand.

This silvicultural technique may appear complex and impractical. Field crews can soon estimate the d.b.h. and spacing of most trees well enough by eye, measuring only those near the limits. In Sarawak, where the system has been applied to thousands of hectares, crews have abandoned the layout of plots and judge crop-tree spacing on the basis of their initial experience with the plots.

The results of the treatment in terms of yields and financial returns are as yet unknown. The initial treatment may require 5 d/ha with a crew of three. Later treatments, with the painted crop trees still identifiable and fewer trees to be removed, require less time.

In Sarawak, the similar technique is termed "liberation thinning." Crop trees are selected in cutover stands of hill dipterocarps. Each is then liberated by reducing the basal area surrounding it to stimulate rapid growth, somewhat as in Puerto Rico (Hutchinson 1980). This treatment has almost immediately stimulated the growth of the trees that were left with overhead light (table 4–14; Bryan 1981). The mean growth increase was 29 percent; trees that had been overtopped increased 125 to 160 percent.

Improvement fellings have not always lived up to expectations. The assumption that such treatments would accelerate the growth of good trees in the residual stand and stimulate regeneration of select species as needed has not everywhere proved valid. More proof is needed that manipulating the canopy to improve the crown position of a large tree will increase growth, or even that reducing the surrounding basal area will have a similar effect.

In Philippine dipterocarp forests, results of improvement fellings reportedly have been more favorable. Treatment of residuals by cutting climbers, girdling defectives, and liberation increased growth of selected trees threefold and promised a shortened cycle (Utleg and Reyes 1967). But in Sabah, during the first 5 years after release of an existing crop, growth acceleration of large trees proved disappointing (Fox 1972). Nevertheless, saplings of 10 cm in d.b.h. or less did respond to release.

Application of Hutchinson's (1993a) liberation thinning to mixed secondary forests in Costa Rica has produced further evidence of early growth acceleration as a result

Table 4–14.—Response of dipterocarps to liberation in Sarawak (cm)

D.b.h. class	4-year mean annual d.b.h. growth	
	Unliberated	Liberated
10–14	0.57	0.79
20–24	0.52	0.72
30–34	0.54	0.72
40–44	0.61	0.79
50–54	0.71	0.88
60–64	0.81	0.98

Source: Bryan 1981.

of treatment. Basal-area increment as a percentage doubled in 17 months.

The jury is still out on the magnitude and duration of the effects of liberation, but recent studies continue to indicate that liberated crops mature faster than those not liberated. Uebelhor and others (1989) report that liberating Philippine dipterocarps from crown competitors reduces rotations at 60 cm in d.b.h. by 10 to 15 years, the benefits being greatest among small trees. The International Tropical Timber Council (Anon. 1990b) reports that 8-year results of liberating hill dipterocarps in Sarawak suggest cutting cycle reductions of 5 to 10 years.

In Nigeria, postlogging climber cutting and poisoning in the middle of the upper canopy liberated 16 economically valuable species (table 4–15; Henry 1956). The number of large trees renders the decrease in regeneration unimportant.

A study of two liberated 0.1-ha plots in a subtropical, wet forest in Puerto Rico shows rapid acceleration (Anon. 1953b). Immediately after liberation, there were 1,961 trees per hectare more than 5 cm in d.b.h., with a mean d.b.h. of 12.2 cm and a basal area of 23 m^2/ha. Five years later, there were 2,601 trees per hectare (ingrowth of 640) and a basal area of 30 m^2/ha. Mean annual d.b.h. growth was 0.34 cm/yr for all trees and 0.58 cm/yr for dominants and codominants alone. Volume rose from 101 m^3/ha to 140 m^3/ha, or 7.8 m^3/ha/yr.

Another early test, in Guyana (John 1961), determined the mean growth of three canopy classes of *Virola surinamensis* during 18 months following liberation (table 4–16). In this study, contrary to the one in Nigeria, the subordinate trees accelerated their growth faster than the dominants.

In Suriname, poisoning of undesirables down to 10 cm in d.b.h. stimulated growth of all trees up to 50 cm (Schulz 1960). Some of the rapidly growing trees, such as *Goupia glabra* that are 5 m or more in height, may be released adequately with one treatment. For smaller trees, the treatment must be repeated, especially for strong light demanders, such as *Schefflera morototoni* and *Simarouba amara* (Schulz 1967). Eliminating the overstory can increase the height growth of saplings and poles of the desirables tenfold.

Synnott (1979), reviewing general results but especially those of Africa, concluded that felling or poisoning normally results in faster mean growth on all the remaining trees, including leading desirables and individual species groups. In one case, the faster growth of remaining trees more than offset the effects of reduced basal area, so that net basal-area growth increased as original basal area was reduced.

Liberation, and in fact all refinement treatments, are costly and conducive to only distant future returns. An analysis in Sarawak, however, adds an important dimension to those benefits. Laursen (1977) concluded that the increased growth from liberation in cutover residuals in Sarawak could ultimately generate 10 days of employment per year in primary processing for every day of work dedicated to treatment.

Thinnings. Thinnings are fellings made in immature stands, primarily to increase diameter growth but also to

Table 4–15.—Postlogging changes in a Nigerian stand of 16 economically valuable species liberated by climber cutting and poisoning in the middle of the upper canopy

Tree size		No. of trees per hectare	
Height (m)	D.b.h. (cm)	Immediately after logging	6 years later
0–1	—[a]	51	23
1–3	—[a]	118	36
3	10	63	129
—[a]	10–60	19	34

Source: Henry 1956.
[a]Not measured.

Table 4–16.—*Virola surinamensis* response during 18 months following liberation in Guyana (cm/yr)

Canopy position	Mean annual d.b.h. growth	
	Untreated	Treated
Below canopy	0.37	0.54
Canopy	.61	.88
Emergent	.87	.99

Source: John 1961.

improve the form of the remaining trees (Ford-Robertson 1971). Despite this broad definition, the term "thinning" is generally applied to stands where the trees are all about the same size, typically even-aged plantations. Thinnings are thus concerned with lateral competition among trees of about the same height in contrast to liberation, which reduces competition chiefly from above. In secondary forests, only young volunteer stands or local groups of trees are of uniform size, so thinning is only one of several purposes of improvement fellings in such forests. Nevertheless, the results of thinning in secondary forests are usually reported with those of liberation, because in irregular stands, the two are inextricably mixed.

Thinned forests, at least those of the Temperate Zone, reportedly respire less relative to assimilation than unthinned forests and thus may grow faster, in part, for that reason (Assman 1970). In the Tropics, where rapid respiration significantly decreases net primary productivity, this benefit of thinning might be accentuated. Thinning also shifts growth to the lower part of the stem, increasing taper.

Recognition that thinning should be an integral part of refinement developed early. In Malaysia, removal of relics over a new crop proved inadequate to stimulate growth, thus thinnings were needed in addition (Wyatt-Smith 1963). In Sabah, girdling noncommercial and defective commercial trees down to 5 cm in d.b.h. was prescribed in 1965 to open dense clumps (Nicholson 1965b). Early selection fellings in Nigeria included thinning of desirables (Osafo 1970).

One limitation of thinning is the effect of opening the canopy. Extremely heavy thinning can encourage unwanted opportunists and climbers. In evergreen hill forests in Thailand, opening the canopy more than 30 percent on 20 to 25 percent slopes also led to serious soil erosion (Ruangpanit 1975).

A guide to the degree of thinning that should stimulate growth increases was offered by Palmer (1975), who suggested maintaining the basal area at less than two-thirds of the maximum. Where there is a market for thinnings, such treatment could be profitable. A basal area of about 25 m^2/ha has been recognized as a maximum for rapid tree growth in mixed broadleaf forests of the lowland Tropics (Dawkins 1961b). As was indicated in the prescriptions for Puerto Rico, even lower limits may apply to small trees. There is no evidence that these limits can be increased by technology, although virtually no attempts have been made.

In Ghana, high stand density retards growth, whereas medium density favors export-market shade bearers and low density favors rapidly growing light demanders (Danso 1966). Well-regulated, frequent thinnings are needed. Eliminating only the noncommercial species does not necessarily result in early crown building on the commercial ones.

Arboricides. The use of chemical herbicides to kill trees in the Tropics apparently was introduced from the Temperate Zone. Sodium arsenite, despite its extreme toxicity and the occasional loss of human lives associated with its use in forestry, was applied throughout much of the Tropics in the past. Its use continued even long after the advent of other herbicides that were safer to use and less persistent as environmental pollutants. There were several reasons for this continued use. In Ghana and Sierra Leone, sodium arsenite was more effective and less expensive (Anon. 1958f, Pickles 1958). King (1965) favored it because of balance-of-payment advantages in not having to import the solvent. As a soluble powder, it was easy to transport and mix with locally available water.

In forests in what is now Malaysia, sodium arsenite killed 70 to 80 percent of the treated trees within 12 months (Strugnell 1937, Wyatt-Smith 1960b). In one test of trees 30 to 90 cm in d.b.h., other chemicals killed only 25 percent of the trees after 21 months and were particularly ineffective on large, thick-barked, buttressed trees.

Sodium arsenite was also more reliable in wet weather than some other arboricides (Dawkins 1961b). Sodium arsenite has disadvantages other than its toxicity.

Whereas King (1965) favored its rapid kill, Durant (1936) and Dawkins (1958a) considered it too effective in this regard, producing a sudden brief opening of the canopy rather than a gradual, more durable one. Also, arsenite does not usually kill unless complete frills are cut, a step that is difficult with some trees and not necessary with some other arboricides.

Organic arboricides have been available for decades. Many chemicals, including sodium arsenite, have been withdrawn because of environmental hazards and others are suspect. Only broad observations are cited here. Local trials must precede widespread application.

In Uganda, many trees were killed in 5-1/2 months simply by applying diesel oil to frills (Dawkins 1958a). Applications from December to February seemed to work faster than those from March to August.

In what is now Malaysia, 3 percent solutions of 2,4-D mixed with 2,4,5-T and 5-percent solutions of 2,4,5-T alone, both in diesel oil applied on unbroken bark did not kill large buttressed trees (Wyatt-Smith 1960b). On frill-girdled bark, a 2-percent solution of 2,4,5-T was also ineffective on large trees. Of the trees 30 to 90 cm in d.b.h., only 25 percent were dead 21 months after treatment. Spray treatments on unbroken bark were also found ineffective in francophone Africa (Catinot and Leroy-Deval 1960). (2,4,5-T has since been withdrawn from the U.S. market.)

In Puerto Rico, the effectiveness of organic arboricides has varied among tree species. Particularly resistant are members of certain genera such as *Mangifera* and *Eugenia* (Myrtaceae).

Killing bamboo is desirable under some circumstances. One species *(Bambusa gigantochloa)* has been killed by basal application of sodium chlorate (20 percent solution), TCA (10 percent sodium trichloroacetate), dalapon (5 percent), and amatrole (5 percent); amatrole was the most effective (Burgess 1975).

Recent concern over secondary environmental damage from chemical treatments has questioned the silvicultural use of arboricides. Possible side effects on soil and aquatic organisms and higher animal life have been cited. Even accelerated loss of nutrients has been suggested (Barclay-Estrup 1972). The fact that manual methods of removing unwanted vegetation provide more manual employment than chemical methods is also cited as a drawback of arboricides. Some of the concern is with silviculture per se, including complaints that removing understory vegetation removes cover and food for wildlife. Removing "inferior" species is also questioned on the basis that they may make some contribution to the ecosystem and might become marketable.

Use of chemical arboricides in silviculture must not be impetuous; it must be rationally defensible. Any potential hazards should be well understood and demonstrably tolerable. The primary objective of silviculture is to maintain or improve the site; this requires a concern for the whole ecosystem that transcends the need for commodities. When serious doubt as to the superiority of arboricides exists, the most prudent course may be to use girdling without the use of chemicals.

Any silvicultural program using arboricides must incorporate two features: safety and research. Safety measures must reflect a thorough knowledge of the chemical properties of the products and prescriptions for their use to avoid serious hazards to human society. Research should address both the effects, direct and indirect, of any herbicide and ways to make applications safer and more cost-effective.

Yields

Silvicultural treatment of secondary forests was initially intended to eventually yield a profit (Barnard 1954). However, comparing secondary-forest production with that of other crops led to the conclusion that in Malaysia, maintaining forests purely for their productivity is questionable (Wycherley 1969).

Yield data from treated stands are not yet adequate to define the upper limits of timber productivity in secondary forests. Meanwhile, opinions differ widely. Some have assumed that yields from managed natural forests will ultimately equal those from plantations of the same species on similar sites (Poore 1968). Others (Leslie 1977) have expressed doubt that even the most optimistic silvicultural projection can improve the economic performance of natural forests enough (relative to other forms of land use) to justify their management solely for wood production.

Refined moist secondary forests containing the most productive species seem capable of yields of 4 to 10 t/ha/yr of stemwood, 50 percent more if branchwood is included (Dawkins 1964b)—the difference from untreated forests being more in quality than in quantity. Results vary widely with stand history. Wyatt-Smith (1987a) concluded that a tropical moist forest, on the average, yields up to 2 m^3/ha/yr; silvicultural treatment can increase this to about 6 m^3/ha/yr. Lowe (1984) concluded that a natural high forest in Nigeria could produce only 40 m^3/ha in 40 years. Productivity of a dipterocarp stand in the Philippines after removal of 9 to 15 percent of the timber trees, ranged between 5 and 6 m^3/ha/yr (Miller 1981). Yet, removing 23 percent of the timber trees caused such damage to the residual stand that postlogging mortality offset growth for 7 years. In the wet lowland forests of Colombia, natural regeneration 15 years after cutting was yielding 54 m^3/ha of pulpwood from trees 10 cm in d.b.h. or more, an average of 3.6 m^3/ha/yr (Ladrach 1983).

Although timber yields from secondary tropical forests may be lower than those of the best plantations, investments required may also be lower and are often more in tune with available financial resources (Palmer 1975). With dipterocarps in Sarawak, liberation thinnings were said to promise a second harvest in about 30 years compared with a wait of 60 years or more without treatment (Hutchinson 1980).

The difficulty in quantifying potential productivity of secondary forests, particularly when compared with pure plantations in terms of volume yield, complicates justifying silvicultural treatment. In the absence of annual rings, reliable growth data are rare, and those that are available can seldom be applied with certainty to many sites and species or attributed largely to treatment. Data for unmanaged stands generally compare unfavorably to those for well-managed plantations, but the intensive care that plantations normally receive makes such comparisons invalid. Such comparisons on the basis of volume may also be invalid because the products of secondary forests may have a higher intrinsic value per unit of volume than those of plantations.

Trees in untreated secondary forests indeed grow slowly. A basic limitation of most tropical angiosperms is the requirement of low stocking for rapid growth (Dawkins 1961b). Rapid growth requires direct illumination of tree crowns, a condition that for most tropical trees in untreated forests either never exists or endures only briefly after a natural catastrophe. Thus, as secondary forests increase in basal area toward a maximum, tree-diameter growth declines. The disappointingly slow growth rates are apparently universal, having been reported from India (Khan 1946, Page 1948), Fiji (Cottle 1957a, 1957b), east Africa (Pudden 1957a), the Sudan (Jackson 1960), Guyana (John 1961, Prince 1973), and Puerto Rico (Crow and Weaver 1977).

In cutover forests in Nigeria, *Khaya grandifoliola,* a tree known for its growth potential, would require 80 years to attain 50 cm in d.b.h. (Dawkins 1961c). Diameter-growth rates of marketable species in a rain forest in northeastern Australia averaged less than 0.2 cm/yr (Haley 1954). Early tests in Kenya with a variety of indigenous tree species showed their growth too slow to be considered economical (Anon. 1952h).

In the Western Hemisphere, *Virola surinamensis* in Guyana grew for 20 years after logging at average rates of 1.3 cm/yr for emergents, 0.9 cm/yr for canopy trees, and 0.6 cm/yr for those of the understory (John 1961). Similarly, *Ocotea rodiaei* in Guyana averaged 0.4 cm/yr (Prince 1973). In Puerto Rico, 18-year records of 20 species in cutover forests showed that annual d.b.h. growth of dominants and codominants averaged less than 0.8 cm/yr (Crow and Weaver 1977).

It is readily apparent that higher yields will be required from natural forests in the Tropics. One approach is to concentrate management on the most productive sites. Another is to increase marketability of little-used, fast-growing species. Whatever the approach, it must be supplemented by liberation treatments that stimulate trees to meet their growth potential.

Freshwater Swamp Forests

Swamp forests, those inundated part of the year or with water tables constantly near the soil surface, generally have not received due attention from silviculturists. Their extent, some 160,000 km^2 in South America alone (Lanly 1982), is much less than that of upland forests, but their potential importance as a wood source may be much greater than this would indicate. Many of them are more accessible than remaining upland forests, and they are less likely to be converted to other land uses. But managing these forests for wood production has scarcely been undertaken in the Tropics of this hemisphere.

Particularly neglected are the forests of freshwater swamps. Those fed by river sediments annually enjoy unusual nutrient deposits that should sustain productivity. Ecological studies of some of the *varzea* and *igapó* forests along the Amazon have been made recently, but only a few timber species have been utilized.

Peatswamp forests are extensive in Malaysia, particularly in Sarawak, where they are forested with *Shorea albida,* a dipterocarp that produces useful timber, although many old trees are hollow. Cutting of swamp forests in some places is controlled by area and girth limits, but no formal silvicultural studies have been conducted. Slow growth has been reported from such forests in what is now Peninsular Malaysia (Wyatt-Smith 1961b).

Mangroves

The systematic management of mangroves apparently began in what is now Malaysia in 1904 (Kader 1979). Seventeen principal mangrove tree species and 23 secondary species were described there nearly 70 years ago (Watson 1928). The products extracted have been fuelwood, charcoal, poles, piling, chips, and tannin. Large volumes of chips have been exported from both Sabah and Sarawak (Kader 1979). The mangrove species of greatest commercial importance worldwide are those of the genus *Rhizophora* (Huberman 1959), although in Indonesia, the preferred timber species have been those of the genera *Avicennia* and *Sonneratia,* followed by those of *Bruguiera, Rhizophora mucronata,* and *R. spiculata,* (Versteegh 1952).

From afar, mangroves may appear uniform, but in fact, they vary widely within short distances in response to soil types, levels and quality of floodwater, tides, salinity, and the degree of protection from marine currents and wave action. These differences have been classified for tropical America (Lugo and Cintron 1975). However, most discussions of mangrove management pay little attention to these fundamentals. An exception is the description by Noakes (1952) of *Rhizophora* forests in what is now Malaysia. He stated that *Rhizophora* thrives there in areas inundated by ordinary high tides but with dry periods of 4 to 8 days at each neap tide. It does well in soil aerated and enriched by pioneer species but will not thrive on stiff clay, requiring at least some sand and streams nearby.

The culture of mangrove forests has been chiefly concerned with how to extract wood economically without jeopardizing future productivity. Cutting practices include minimum girths, clearcutting with or without seed trees, shelterwood, and coppices. The selection system was dismissed in what is now Malaysia because transport difficulties dictated light harvests of low value (Finlayson 1951, Watson 1928).

A shelterwood-coppice system was proposed for mangroves in India (Hall 1937). From 220 to 250 standard trees 20 cm in d.b.h., or 100 to 125 standards 30 cm in d.b.h. were to be selected and all other trees felled. The standards were to be removed a few years later after the coppice had developed. The results apparently were not reported.

Two-story mangroves, with cutting every 20 years, a system favored for what is now Malaysia by Watson (1928), resulted in serious felling damage to the understory (Anon. 1948c). On a 4-ha plot, removing 247 trees per hectare more than 20 cm in d.b.h. left only 140 undamaged, or 38 percent of the 370 trees per hectare between 10 and 20 cm in d.b.h. Of these, about 90 were in dense clumps where little cutting was done, leaving only about 50 trees per hectare scattered elsewhere. Experiences such as this sparked interest in clearcutting after the presence of a heavy seedling crop was confirmed (Hodgson 1932).

The development of cultural practices reached an advanced stage in the mangroves of Perak, in what is now Malaysia (Noakes 1951, 1952, 1957, 1958). Minimum girth fellings, tried at the outset to 10 to 12 cm in d.b.h., yielded a harvest of trees averaging 14 to 24 cm in d.b.h. This system resulted in good regeneration of *Rhizophora* except for blank areas that were costly to plant. Leaving a lighter canopy of 10 seed trees or fewer per hectare was then tested. The resulting larger canopy openings favored the less desirable *Bruguiera parviflora.* Both of these methods were later abandoned because of excessive felling damage. The leaving of standard trees, then tried, led to heavy mortality and windthrow. A return to clearcutting continued to favor *Bruguiera* and gave fair regeneration. Where markets are good, thinnings have been guided by the use of a "stick," calling for removal of the poorer of any two trees closer to each other than the stick's length. In stands 10 to 15 years old, a stick 1.2 to 1.5 m long was used. At 20 years, the stick was 1.8 m long, and at 25 years, 2.1 m. This ingenious technique requires minimum supervision.

In Thailand, removal of all mature trees left areas nearly open; therefore, a type of shelterwood, retaining overstory shade, has been applied (Banijbatana 1958). *Avicennia alba,* which was found to be a light demander and poor coppicer, has been regenerated in Adhra Pradesh, India, by clearcutting (Khan 1960).

In the Western Hemisphere, mangrove harvesting has rarely been concerned with future productivity. However, experimental clearcutting of *Laguncularia racemosa* in Puerto Rico in strips 20 m wide and perpendicular to the prevailing wind produced a new, fully stocked generation in 2 years (Wadsworth 1959). There was no perceptible damage from windthrow along the edges of the strips. A young stand of trees averaging 4.3 cm in d.b.h., thinned from 34 to 14 m^2/ha basal area, doubled its mean d.b.h. growth in 3 years. Growth acceleration was general, even on trees whose canopy position had not changed.

A management program was developed for the Tamavenca mangrove in Venezuela (Luna 1976). The average number of trees 8 cm in d.b.h. or more was 428 per hectare, with basal area ranging from 10 to 40 m^2/ha, and average volume about 200 m^3/ha. Clearcutting was prescribed for alternate strips 50 by 300 m; the remaining strips were to be cut after 15 years. The trees were to be used for utility poles, sawtimber, parquet, particleboard, charcoal, and tannin.

The wetness of swamps, generally, and the salinity of mangroves preclude a sharp change in the composition of successive forests after human intervention. The main concern in regeneration is usually numbers rather than composition.

Mangroves are generally prolific seeders, and *Avicennia* (except *A. alba* in India [Khan 1960]) and *Laguncularia* coppice freely. *Rhizophora* may also do so when young (Noakes 1958). The seeds of *Rhizophora* are viviporous; i.e., they germinate on the parent and are released ready to take root. Others, such as *Avicennia* and *Laguncularia,* produce seeds that are so readily waterborne that, where flooding is frequent, clearings need not be close to seed trees. Fruiting of *Rhizophora* in what is now Malaysia begins in the 4th year (Noakes 1952). In Perak, in what is now Malaysia, *Rhizophora* natural regeneration was common beneath the trees but irregular elsewhere. Some of the gaps left after felling did not regenerate for 10 years. Failures of the *Rhizophora* regeneration may be due in part to drifting slash and the difficulty new hypocotyls have in penetrating through it to the soil. Seedling regeneration of *Laguncularia racemosa* in Puerto Rico surpassed the height of coppice shoots by the 9th year following clearing (Wadsworth 1959).

Planting *Rhizophora* in unregenerated areas has been a standard practice in Indonesia (Versteegh 1952). Bare spots are planted up to 2 years after felling. *Rhizophora* seeds are commonly collected on the ground. Wildlings 60 cm tall have also been used successfully in Puerto Rico (Holdridge 1938). Damage to planted seedlings by crabs was reported in what is now Malaysia (Noakes 1952). In Thailand, trees were protected from crabs by wrapping the hypocotyls in plastic sheeting (Anon. 1976i).

The giant fern *Acrostichum aureum* is a problem because it tends to spread into open areas within mangroves and may interfere with regeneration. The fern develops two forms, one large and one small (Noakes 1952) and responds rapidly to full light. If no tree seedlings are present when it invades, none can get in later unless there are seed bearers standing directly over the area. This threat was one of the early arguments for retaining a shelterwood because the fern reportedly was easily controlled by light shade (Finlayson 1951; Noakes 1951, 1952). Removing it is impractical because it is intimately mixed with established seedlings (Noakes 1958). Periodically, in what is now Malaysia, the fern acts as a "nurse" to seedlings already established within it (Noakes 1951).

A handbook for mangrove area management is available, summarizing policies, planning, timber management, rehabilitation, regeneration, and economic considerations (Hamilton and Snedaker 1985). Research methods are outlined in a second recent publication (Cintron and Schaeffer-Novelli n.d.).

Despite the apparent rapidity with which mangroves recolonize a cleared site, individual tree diameter growth within unthinned stands is slow. In what is now Malaysia, diameter growth of trees less than 10 cm in d.b.h. was found to be less than 1 cm/yr; for larger trees, it was less than 0.5 cm/yr (Noakes 1958). Mean annual volume growth culminates at about 25 years; the maximum on the best areas is about 10 m^3/ha/yr; the average is much less. Trees 12 to 25 cm in d.b.h. have a rotation of 30 years (Noakes 1957). Rotations formerly 30 to 50 years have been reduced to 20 to 30 years to meet growing fuelwood demands. Yields in the Matang mangroves of Peninsular Malaysia at 30 years ranged from 3.5 to 7.8 m^3/ha/yr of firewood plus thinnings (Christensen 1983).

Mangroves in Fiji have been compartmented and worked on a 40-year rotation for poles (Anon. 1950c). Stick thinnings have been made at ages 15, 25, and 35, using stick-lengths of 0.9, 1.5, and 2.4 m, respectively.

In tropical America, the growth of mangroves has been found no more rapid than in the Eastern Hemisphere. In Puerto Rico, a pole-size stand of *L. racemosa* had, over a period 3 years, an average d.b.h. growth of 0.46 cm/yr for dominants, 0.40 cm/yr for codominants, 0.24 cm/yr for intermediates, and 0.17 cm/yr for suppressed trees (Wadsworth 1959). A 14-year record in the same stand gave a mean of 0.37 cm/yr for *L. racemosa* and 0.29 for *Avicennia germinans* (Weaver 1979b).

Dry Forests

Dry forests, those classified by the Food and Agriculture Organization (FAO) (Anon. 1993b) as dry deciduous, very dry, and desert forests, make up some 14 percent of the world's tropical forests and 5 percent of those in tropical America but have generally been neglected. They are concentrated mostly in Africa and Asia but are also common on the Pacific slope of Central America, in eastern Brazil, and in other parts of tropical America, such as the Gran Chaco of Paraguay. Foresters tending dry forests in Africa and Asia have had some success with coppicing and fire protection.

Probably the longest record of study of dry forests has been in India. In Madhya Pradesh, dry deciduous forests have been satisfactorily managed since the 1830s by the coppice-with-reserves system, in which quality trees are left to grow for two coppice rotations (Sagreiya and Nath 1968). Where the trees were protected and tended, their value increased rapidly. Site quality improved and the principal species regenerated. In contrast, where pole crops were overcut or fires or grazing were not controlled, the crops regressed.

The coppice-with-reserves system arose out of imperfections in the former coppice-with-standards system, applied in India since 1905 (Chaturvedi 1963). The main difference is a lessening of the distinction between the two stories; under the newer system, the upperstory can include good trees of almost any size. The system was designed to meet demand for small- and medium-sized timber, poles, fuel, and fodder. The rotation is commonly 30 to 40 years, with thinnings at 15 to 20 years. Most of the regeneration for both stories is in coppices, although seedlings, where available, fit into the system.

The coppice-with-reserves system was used (Tiwari 1968) where: (1) the valuable species are scarce but are vigorous coppicers and light demanders, and (2) there is a clear reason for coppicing, such as badly malformed stands.

Coppices are not applicable where: (1) the valuable species are shade bearing; (2) there is a danger of invasion by rapidly growing, obnoxious trees, weeds, or grasses; (3) species composition will not be improved; (4) there is little demand for the felled trees; and (5) protection from fire and grazing is impossible.

In Pakistan, riverine dry forests of *Dalbergia sissoo* were stimulated to regenerate by suckering along trenches dug 25 cm deep within 12 m of each *D. sissoo* stump (Paul 1953).

In the upper Nile, leaving seed bearers when cutting the forests and then burning after the rainy season produced a dense crop of coppice and seedlings of *Acacia* and *Zizyphus;* even so, a heavy grass cover may follow (Anon. 1954a). Elsewhere, in the savannas of Sudan-Guinea, protection from fire for 10 years alone was enough to produce crops of poles and firewood adequate to supply the local population (Tilton 1961). The germination of *A. senegal* in such areas was stimulated by increased dry-season rainfall; frequent light showers are as important as the total amount of precipitation (Obeid and Seif el Din 1971).

In the dry regions of Uganda and northern Nigeria, total exclusion of fire appears to be the only way to encourage reinvasion of forests (Anon. 1952m). In Nigeria's *Isoberlinia* woodlands, protection from fire has also improved canopy development and diversity. In the adjacent savanna zone, fire protection led to a thicket in 10 years (Anon. 1951b). The soils are too poor for forest plantations and must remain in native forests to protect the soil and water (Kemp 1963). Cutover areas may be cultivated at the end of the wet season, but must thereafter be protected from fire for 10 years in order to produce a new stand. Even then, fall burning will ultimately wipe them out. Spring burning, on the other hand, is tolerable. Natural regeneration is by coppice and sucker shoots (Paul 1953).

The extensive miombo (dry forest) woodlands of the east African uplands are physiognomically similar to the forests of twisted trees in the Brazilian cerrados, although the former reflect primarily climatic influences and the latter, soil effects. In the Copperbelt of Zambia, formerly Northern Rhodesia, these forests are believed to have been stable for the past 500 years (Fanshawe 1956a, 1956b). Some 90 percent of the area has been cultivated for food crops in the past. Fires sweep through almost the entire area every year. When the forest is cut for mine timbers, poles, posts, or fuelwood, seedlings are generally waiting and may survive, but they grow more slowly than the sprouts. Root suckers are successful if the fires have not been too hot; they may produce two or three crops on a 40-year rotation. A 5-year study in the miombo of Tanzania showed seedling regeneration to be best with no burning and next best with alternate years of late burning and no burning (Kimber 1963).

An experiment in the Copperbelt of what is now Zambia compared three treatments: (1) conventional exploitation for mine timbers; (2) removal of all firewood, leaving only crop trees; and (3) conversion to a selection forest. Treatment (2) resulted in the greatest increase in growth after 20 years (Storrs 1956). However, growth rates began to decline after 10 to 15 years, suggesting a need for further treatment. When 12 to 50 standards were left per hectare and the rest of the forest was felled, the standards respond well with more rapid growth (Fanshawe 1956a).

As silviculture of the miombo forests developed, both site and market distinctions were made. On especially good sites, the forests have been converted to plantations of pines, eucalyptus, and other rapidly growing, broadleaf species (Fanshawe 1960). Elsewhere, depending on site quality, the native forests have been managed for firewood, smelter poles, sawtimber, or all three. Early burning was done to protect areas from more destructive late fires. Coppice shoots may not appear for up to 5 years after a serious burn. About 40 percent of the stand coppices successfully. The canopy closes after 25 to 30 years.

Firewood crops in the miombo forests have been harvested at 40 years. Smelter poles and sawtimber have been produced as standards on rotations of 60 to 100 years, with coppices beneath but only on fairly good sites. Growth rates average 0.05 to 0.20 cm in d.b.h. per year for dominant species but may range up to 0.5 cm/yr during the first 30 years. Final crops contain 125 trees per hectare, of which 12 to 60 may be standards. Average and maximum rotation yields per hectare are 4 to 24 m^3 of sawtimber, 12 to 25 smelter poles, 100 to 250 small poles, and 140 to 200 m^3 of fuelwood.

Management of native dry forests in tropical America has rarely been attempted. There is ample evidence that indiscriminate felling, burning, and grazing deteriorate or destroy these forests. More than 35 years ago, Petrak (1959) noted the deterioration of quebracho *(Schinopsis balansae)* forests of the Argentine Chaco due to cutting and grazing. He saw no physiological obstacles to maintaining the forests if heavily shaded areas were opened up. On some of the better sites in Minas Gerais, Brazil, it appears that forest plantations can be much more productive than the native forests, at least for one rotation. Brazil's campos and cerrados have long survived in the face of heavy fuelwood drain because of their coppicing power. Nearly all of the more useful tree species regenerate by sprouts (Barros 1965–66).

An interesting proposal for the use of dry forests for energy production was made in the Dominican Republic (Trehan and others 1980). A 50-megawatt power plant would be supported by wood fuel from 78,000 ha of land considered unsuitable for agriculture. The source would be dry forests composed largely of *Acacia, Leucaena,* and *Prosopis.* A yield of 5 m^3/ha/yr was assumed, and post-establishment employment was predicted to be approximately 1,000 persons.

Conclusion

This chapter has dealt with a subject having many diverse facets. Secondary tropical forests are little appreciated, yet there have been decades of efforts to assess their present and potential productivity. There persists a perception that unless their volume yield compares favorably with the yields of managed plantations, they are a submarginal investment. Such a perception clearly underestimates the potential benefit-to-cost ratio of the management of, at least some, secondary tropical forests. It ascribes no value to the diversity of such forests not found in plantations. It assesses the returns of management on the basis of timber alone. It makes a judgment on the basis of past efforts, some producing conflicting results, to produce a small fraction of the forest products that have since become marketable. It sees labor intensity as a cost rather than a social asset. The experience reported here is extremely diverse and much of it far from tropical America, but it suggests new approaches that might be more appropriate under present local conditions for providing the variety of forest products that tropical peoples will need and that cannot come entirely from the much less extensive area of plantations. Predictions of yield limits and their value under past conditions are undoubtedly low. The reader is encouraged to further the studies and testing that could lead to a complete reversal of the present conservative assessment of the potential productivity of these forests.